Life Cycle Assessment of Energy Conservation Measures during Early Stage Office Building Design: A Case Study in London, UK

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Abstract

Embodied versus operational environmental indicators are often studied in isolation. This paper presents a cradle-to-grave Life Cycle Analysis of energy conservation measures for a planned large, medium-rise office building in central London, UK with Gross Floor Area of 15,590 m^2 and a 60-year building lifetime. The original design complied with the UK Building Regulations Part L, achieving 40% operational carbon emission savings compared to Target Emissions Rate. The LCA solutions focused on structure, envelope, and operational systems. Embodied energy saving strategies encompassed the application of lean design principles and integration of low carbon materials. Operational energy saving techniques included the adoption of a fabric-first approach, adaptive thermal conditions and sustainable building systems. Cumulatively, these optimization strategies achieved a maximum of 16% and 13% savings on life cycle carbon and energy, respectively, compared to the original design. Embodied strategies saved 32% and 9% on embodied carbon and energy, respectively, while operational strategies reduced the original consumption by 14% on both indicators. Over a 60-year building lifetime, operational energy was 10 times higher than embodied energy, while operational carbon was 8 times higher than embodied carbon. The study findings have highlighted the significance of LCA for early stage building design decisions.

Abbreviations

CLT – Cross Laminated Timber; *BIM* – Building Information Modelling; *BRE* – Building Research Establishment; *BREEAM* – Building Research Establishment Environmental Assessment

1 | Introduction

Methodology; *IESVE* – Integrated Environmental Solutions Virtual Environment; *LCA* – Life cycle Assessment;

Keywords

Life cycle Assessment, Life cycle Analysis, embodied energy, operational energy, design optimization, office building

1 Introduction

The building construction sector is responsible for the consumption of 40% of all fossil fuels, 30% of raw materials, 25% of water and 12% of land worldwide. It generates 25% of solid waste and emits 33% of greenhouse gases [1], thus increasing the risk of energy scarcity and accelerating human-made climate change. The combined impact of finite resource depletion and pollutant release necessitates an understanding of life cycle energy and pollutant flows associated with buildings. In the UK specifically, building construction and operation contribute to half of UK's carbon emissions [2] with an annual 1.5% increase trend [1].

The construction industry and respective building regulations have yet to acknowledge the importance of the life cycle environmental impacts of construction products. Increasingly stringent energy efficiency policies enforced by the Energy Performance of Buildings Directive (EPBD) [3] in Europe and Part L of the Building Regulations [4]–[7] in the UK only address the operational aspect of building life cycle impact. They do not consider the impact of manufacturing, transport and building construction processes that contribute 10% of UK's greenhouse gas emissions [2]. However, the integration of energy efficient solutions into the building envelope may reduce operational demand at the expense of embodied energy and carbon [8]–[10]. Globally, operational energy makes up 70-90% of the total life cycle energy of residential and office buildings [9]. As operational energy is reduced as a result of energy efficiency standards, the ratio of operational-to-embodied energy will decrease. Increasing capital costs of offsetting carbon should incentivise greenhouse gas emissions reductions; these costs were formerly estimated at £12/tCO_2 and are anticipated to increase tenfold by 2050 [11], [12]. Today, the Greater London Authority guidance for preparing energy assessments requires a payment of £60/tCO_2 for a period of 30 years [13]. Assessing the significance of embodied energy and carbon processes could lead to the creation of new environmental laws [14] mandated eco-labelling of construction products [15], and the revision of building performance standards, such as the Building Research Establishment Environmental Assessment Methodology (BREEAM) [14]. Therefore, appropriate benchmarking and a consensus on life cycle indicators, such as means to calculate fossil fuel depletion or global warming potential is necessary. ISO14044:2006 [16] defines Life Cycle Analysis (LCA) as a *"compilation and evaluation of inputs, outputs and potential environmental impacts of a product system (i.e. buildings) throughout its life cycle"*. BS EN 15643-4 [17] outlines the system boundaries associated with a cradle-to-grave LCA, indicating that it includes raw material extraction, transportation, manufacturing, construction installation, use, maintenance, operation and disposal. Integrating early-stage LCA alongside developing technologies and complex building systems is necessary [18]. An awareness about the environmental impacts of construction materials and elements at the conceptual stage, as opposed to retrospectively studying a building LCA post-construction, could significantly influence design decisions [19], [20].

The aim of this study was to develop an understanding of early-stage design solutions to decrease the life cycle energy and carbon intensity of a case study medium-rise office building in London, UK. It investigated the extent to which original designs can be modified and effective design optimization strategies of embodied and operational energy consumption can be implemented. To meet the broader aim, the study's key objectives were: a) To quantify the impact of cradle-to-grave carbon and energy saving techniques in a case study office building in London, UK and assess the feasibility of their implementation; b) To investigate potential correlations between global warming potential (carbon-equivalent) and fossil fuel depletion (energy) for different building elements, specific to the design optimization strategies studied in the case-study building; and c) To develop the capability of assessing interactions between embodied and operational impact in an office building in London, UK. Relating this study to global resource depletion and pollution trends, the identification of the most energy and carbon-intensive building components could lead to the prioritization of material and energy flow reconfigurations within the building sector. The aforementioned broad aims can only be fully achieved, if complemented by a wealth of accompanying LCA studies with similar building function, climate and geographic location. Nonetheless, this case study aims to initiate a methodological framework so that future work can adopt similar strategies.

2 Background

2.1 Existing studies on early-stage LCA

The importance of undertaking early-stage LCA is highlighted in [19], [21]–[23], though limited literature is available on this topic. The existing literature primarily covers residential massing models at preliminary stages, where decisions on the material palette or building form have yet to be made. It is argued that early-stage parametric LCA can predict the maximum embodied savings with minimal inputs known, while its predictions would still be valid at more advanced design stages [24]. The strengths of these studies is that they propose a simple methodological framework to identify which building elements contribute the highest to environmental savings [19], [21]–[23], [25]. Though these prototype studies can be easily applied to other case studies, they only focus on embodied, rather than operational saving strategies. This implies that the resultant building envelope alternatives do not have a standardized thermal performance, which in turn would affect operational loads. None of the studies address feasibility of implementing the best solutions, e.g. maintenance issues, financial viability or installation constraints. Basbagill et al. [19] recommends that designers focus on cladding selection and construction thicknesses over selecting service equipment at early stages. It becomes evident that with little inputs known at the massing model stage, the range of restrictions is effectively inexistent. Thus, the range of design recommendations explored may not be case-sensitive, distorting the importance of different building elements. The case study of Alwan and Jones [12] looks at a more advanced design stage, allowing for feasible solutions with savings of 30% on embodied carbon and 40% on the concrete volume used. However, this study focuses on detailed structural design recommendations limited to an improbable 10 year study period that is not in line with a typical building lifetime, while LCA standards recommend it be 60 years [26]. With a cradle-to-gate system boundary it does not factor the significance of maintenance, transport and disposal [12]. Among the few existing studies about the benefits of early-stage design, the ones at the massing model stage can address more building parameters and environmental indicators [19], [21], while the ones that have already developed plans and material palettes, tend to focus on fewer building elements, typically the most significant, in an attempt to feasibly optimize them.

Unlike the aforementioned studies, McGrath et al. [27] studied the implications of retrofits versus new construction on both operational and embodied energy and carbon for two residential units. Over a lifespan of 50 years the operational stage was found to contribute to 90% and 95% of the entire life cycle for the retrofit versus new build option, respectively. The findings revealed that retrofitting to PassivHaus specifications can save significantly on the operational stage and the envelope environmental footprint, while new construction in compliance with the Irish Building Regulations allows for savings at the end of life stage. However, since the two buildings investigated in this study complied with different building codes and envelope thermal performance, savings attributed to specific optimization strategies cannot be identified. Consistency in such parameters with variation in optimization strategies can allow for a case-specific comprehension of the implications of retrofits versus new builds on life cycle carbon and energy. There remains a knowledge gap with respect to the study of numerous building parameters, while addressing their feasibility of implementation and contrasting embodied strategies to operational design optimizations. Lastly, early-stage LCA for office buildings has yet to be researched, as the focus is predominantly on small-scale residential structures [19], [21]–[23].

Table 1 – Relevant studies addressing early-stage LCA adoption

Reference	Year	Location	Function	Study Period	System Boundary
Geravasio et al. [21]	2014	Portugal	Two-storey residential	50 years	Cradle-to-Use (excl. construction and end-of life)
Basbagill et al. [19]	2013	Confidential	Mid-rise residential	30 years	Cradle-to-Grave (excl. construction, operation and demolition)
Crawford et al. [23]	2011	Australia	House	50 years	Cradle-to-Use (excl. end-of-life)
Alwan and Jones [12]	2014	UK	Observatory/ Visitors' Centre	10 years	Cradle-to-Gate
McGrath et al. [27]	2012	UK	Three-storey residential	50 and 80 years	Cradle-to-Grave

2.2 Statistical analysis assessing the relative contribution of embodied versus operational processes

Figure 1 and Figure 2 summarize a statistical analysis performed on 81 literature sources discussing the building-level significance of embodied versus operational energy. The majority of the literature studied was produced within the last 15 years. Keywords, such as "life cycle", "life cycle assessment", "LCA", "early-stage", "system boundary", "embodied", "office", "commercial" and "UK" were applied to filter the search to office buildings, though a review on their difference to global studies and other residential structures is incorporated. The databases explored include the "Construction Information Service", "Science Direct", "Web of Science", "Taylor & Francis". Ten studies from Asia, 17 from USA, Canada and Australia and 54 within heating-dominated countries in Europe were examined. The analysis revealed the lack of standardization of LCA, which hinders benchmarking. An average of 7.1 GJ/m^2 versus 10.0 GJ/m^2 of building embodied energy is found for the residential versus commercial sector, respectively (Figure 1) [28]. Domestic buildings' embodied energy was also found to contribute towards 22%-26% of the total life cycle energy (Figure 2). The 95% confidence interval for the eight UK studies is high [29]–[34], as results show a range of 3%-80% of embodied versus life cycle energy. The inconsistencies found in the statistical analysis of the studied LCA are attributed to differences in building function, building height, the inclusion of services, such as underground parking [34], and assumed life span (ranging from 25-100 years) [1]. Similarly, it is difficult to directly compare LCA studies due to inconsistencies in expressing results with either primary or delivered energy consumption, the fact that they include buildings in different climatic conditions [1], [9], [34] or with distinct location-based construction technologies etc. [15]. Furthermore, some studies include additional factors within the system boundaries, such as labour-related activities (i.e. nutrition expenses) [35], embodied energy of construction equipment, infrastructure around building (i.e. water pipes, firefighting infrastructure, etc.), city-level assessment (i.e. travel from and to building site) [36]. Last, other studies restrict their LCA to distinct building elements, i.e. structure, envelope or building services [34], [37].

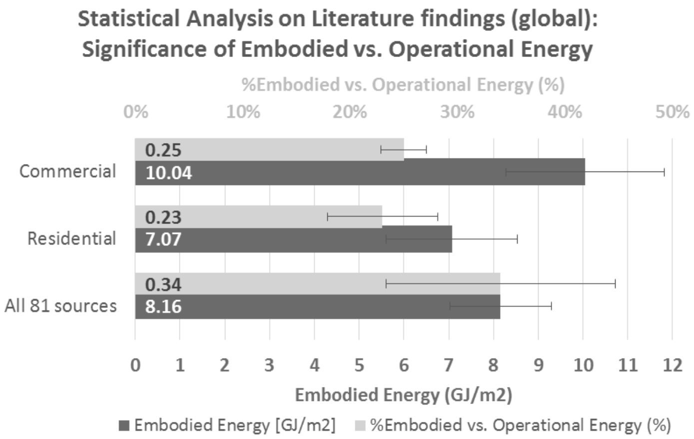


Figure 1 – Statistical analysis of existing studies: Embodied energy vs. operational energy performance

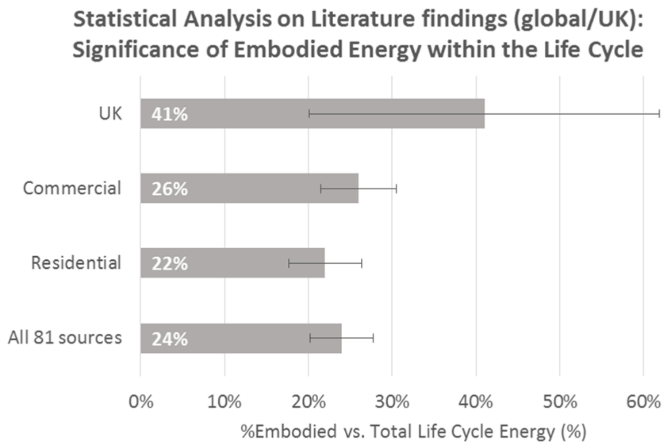


Figure 2 – Statistical analysis of existing studies: Embodied energy vs. total life cycle energy

To summarize, the background section illustrated that existing literature rarely provides contextual comparisons between the magnitudes of embodied versus operational savings. Similarly, office buildings are underrepresented in the field of early-stage LCA. The significance and novelty of this research is that it fills the aforementioned literature gap; the methods of this case study are focused on introducing a prototypical methodological framework, presented as a “palette” of optimization strategies, which pinpoints the best life cycle carbon and energy saving measures to be prioritized. Lastly, the study delves into a range of building elements, rarely studied together, covering, structure, envelope, building systems and operational strategies. The array of building elements addressed allows for a holistic decision-making process to eliminate sources that contribute to the most resource depletion at an early-stage of the design process.

3 Methods

3.1 Case study description

The office building under study is a medium-rise proposed development in Inner London, UK at concept design stage [38]. The architects advocated for the use of traditional materials, e.g. brick, due to the project’s proximity to a heritage site. The total Gross Floor Area (GFA)[1] is 15,590 m^2 and the Net Internal Area (NIA)[2] is 11,550 m^2 (Table 2).

Table 2 - Project specification

Project Data	Structure & Façade	Envelope Thermal Performance (U-value)	Sustainable Strategies (Yearly output per GIFA)
Floors: 11 + LG Avg. floor height: 2.9 m GFA: 15,590 m^2 GIFA[3]: 14,620 m^2 Functional Unit: NIA: 11,550 m^2	Structure: Deep RC piles with RC structural frame and flat slab construction Façade: Brick and traditional construction to respect surroundings	Windows: 1.48 W/m^2K External walls: 0.18 W/m^2K Internal partitions: 1.09 W/m^2K Roof: 0.13 W/m^2K Internal slabs: 1.09 W/m^2K Ground floor: 0.13 W/m^2K	CHP – Combined heat and power: 6.89 kWh/m^2 50m^2 Polycrystalline Photovoltaics: 0.35 kWh/m^2 Chilled Ceilings – thermally massive concrete slabs

The proposed building achieves Part L compliance [6] and was designed as a low-carbon office building, for the operational performance of the building is greatly improved when compared to the notional building. The latter is used to determine carbon dioxide targets, a.k.a. the Target Emissions

[1] Comprises all internal spaces, including the external envelope area, but excluding roof areas [86].
[2] The appropriate functional unit for benchmarking offices is defined as the effective internal floor area of offices, storage spaces, main retail and cafeteria spaces, but excluding service spaces, circulation, columns, parking and plant rooms [87].
[3] Gross Internal Floor Area: Gross Floor Area excluding the area of the outer building envelope [86].

Rate (TER). The notional building is the same size and shape as the actual building, constructed to a concurrent specification, as it follows guidance contained in the National Calculation Methodology (NCM) [39]. This methodology is adopted by Part L [6], [7] and incorporated in the background calculation within IES VE. The Building Emissions Rate (BER) is 14.8 $kgCO_2/m^2$, while the Target Emissions Rate (TER) is 24.7 $kgCO_2/m^2$ GIFA, meaning that the compliant building emits 40% less than the allowed limit. The annual delivered operational energy consumption is 466 MJ/m^2 GIFA [40].

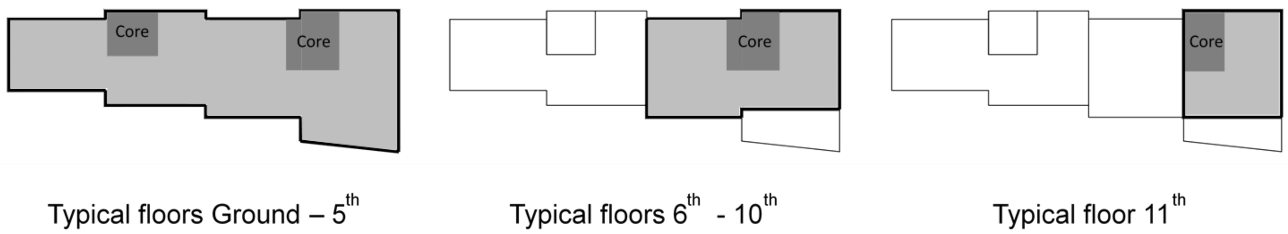


Figure 3 - Typical floor plans for the case study office building (Source: Duggan Morris Architects Ltd)

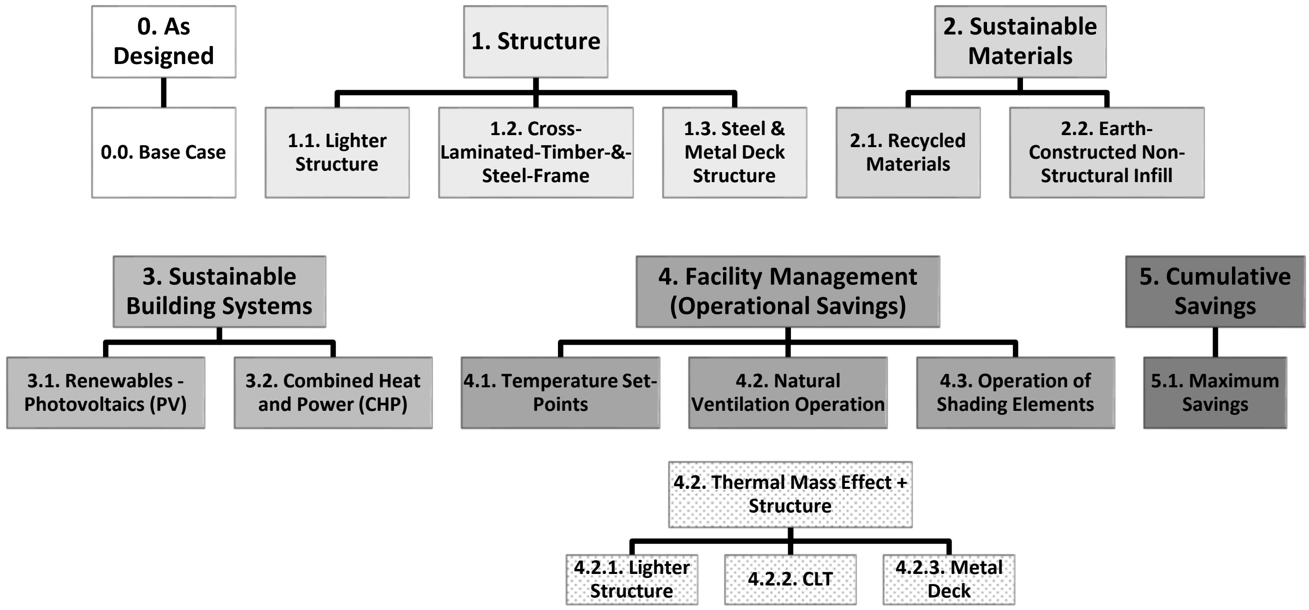
3.2 IMPACT Software and BRE Green Guide Database

Life cycle processes were simulated in this study using IMPACT [41] embedded within IES VE software. This regulation-abiding LCA tool [16], [26], [42] was developed by the Building Research Establishment (BRE) [43] based on its life cycle material database, the Green Guide Book [44]. It incorporates real-life manufacturers' data [45]. The environmental indicators used for this study are fossil fuel depletion, expressed as primary energy (MJ), and global warming potential, expressed as carbon dioxide equivalents (CO_{2-eq}) over 100 years. IMPACT proves most suitable for a comparison of embodied against operational processes, as IESVE is one of the few software packages that both calculate building element quantities automatically and are sensitive to materials' thermal and physical property change. Unlike most LCA software packages, this affects both embodied and operational loads, shifting the significance of one versus the other.

3.3 Modelling of design optimization strategies

The simulation scenarios presented in Table 4 include a wide range of measures to save on embodied and operational energy and carbon in relation to the original proposed design. They represent distinct design philosophies and are, thus, not proportional and non-homogenous in their nature. Changes will only occur in building elements that are applicable to the proposed alteration (Table 3). To maintain consistency across all simulations, all changes to the building elements maintained equal steady-state thermal performance as expressed in U-values (W/m^{2}K). Additionally, each scenario was simulated in isolation to estimate the quantitative impact of the change relative to the base case and emphasize critical areas for re-design. Scenario 5.1 reflects cumulative savings of the most effective measures.

Table 3 - Modelling work plan incorporating the details of the simulation scenarios



Scenario 0.0 - Base case

This scenario represents the initial building design presented in Section 3.1. The advantages of the proposed conventional in situ concrete flat slab construction is its construction simplicity, high thermal storage capacity and low maintenance. Disadvantages are its heavy weight that generally results in larger columns, beams and foundation. The main design also integrates sustainable strategies, such as natural ventilation, PV and CHP. Their impact is investigated in isolation to pinpoint their significance. XPS insulation at 0.03W/mK conductivity is installed in external walls and the ground floor slab.

Scenarios 1.1-1.3 - Structural changes

The following scenarios, impacting both super- and substructure, were adopted in consultation with the structural consultants' RIBA Stage C options appraisals. They considered various other floor framing options using SCIA structural design software, three of which were analysed as part of this study (Appendix 7.3).

Scenario 1.1 – Lighter concrete structure: Through post-tensioning (PT) the concrete slab the slab thickness can be significantly reduced, from 325mm to 275mm. The overall concrete internal slabs volume therefore reduces by 15% (from 3,713m^3 to 4,381m^3) (

Table 4).

Scenario 1.2 – Lightweight Cross-Laminated-Timber (CLT): 100mm internal slabs and steel frame construction to replace the heavyweight reinforced structure. The original 9 m x 9 m grid is maintained; however, 550mm deep secondary beams are added at 3 m centres due to CLT's lower bending and shear capacities. The structural engineer also calculated the steel tonnage for the steel frame and estimated that a 27% savings for the volume of the foundations can be achieved due to the reduced framing weight (Table 4).

Scenario 1.3 – Composite floor (metal deck) and steel frame construction to replace the reinforced concrete columns and slabs. A metal deck with poured lightweight plain concrete supported by 550mm m deep steel beams was proposed. Thus, the steel columns can have a cross section area that is 1/8 of the original concrete design, resulting in 87% volumetric savings due to the material change (from 224m^3 concrete columns to 29m^3 steel columns). Furthermore, the lightweight composite structure renders roughly 27% savings on foundations. The advantages of Scenarios 1.2 - 1.3 is their quicker frame erection, higher savings on material and higher flexibility to modifications. Limitations exist within their lower thermal mass, additional fireproofing required and higher maintenance relative to the base case (Scenario 0.0).

Table 4 – Scenarios 1.1 Lighter concrete structure, 1.2 CLT/steel frame, 1.3 Metal deck/steel frame: Summary of Inputs and assumptions

Building Element[4]	0.0 Base Case	1.1 Lighter Structure (PT)	1.2 CLT/Steel Frame[5]	1.3 Metal deck/Steel Frame
Foundation (**Deep Piles**) Volume	1,950m^3	1,950m^3	1,429m^3	1,475m^3
Construction	RC	RC	RC	RC
%Savings[6]	-	**0%**	**-27%**	**-24%**
Contiguous Piles Volume	448m^3	448m^3	329m^3	339m^3
Construction	RC	RC	RC	RC
%Savings	-	**±0% - unchanged**	**-26%**	**-24%**
Pile Caps Volume	698m^3	698m^3	342m^3	303m^3
Construction	RC	RC	RC	RC
%Savings	-	**±0% - unchanged**	**-51%**	**-57%**
Column Volume	224m^3	227m^3	29m^3	33m^3
Structural grid	9m x 9m	9m x 9m	9m x 9m	9m x 9m
Construction	RC	RC	Galvanized Steel	Galvanized Steel
%Savings	-	**+1.3%**	**-87%**	**-85%**

[4] All data refer to structural properties of the component, excluding cladding, insulation etc.
[5] CLT is modelled as plywood sheets with a higher density, as the BRE database has yet to develop a representative material.
[6] The values reflect material quantity savings rather than construction changes.

Beams/Structural Framing Volume Construction **%Savings**	None (flat slab) - -	None (flat slab) - -	107m^3 Galvanized Steel **+Element added**	77m^3 Galvanized Steel **+Element added**
***Lintels** Volume Construction **%Savings**	71m^3 RC -	71m^3 RC **±0% - unchanged**	71m^3 RC **±0% - unchanged**	71m^3 RC **±0% - unchanged**
***Stairs** Volume Construction **%Savings**	45m^3 RC -	45m^3 RC **±0% - unchanged**	45m^3 RC **±0% - unchanged**	45m^3 RC **±0% - unchanged**
Basement Slab Structural Volume Construction **%Savings**	982m^3 RC -	982m^3 RC **±0% - unchanged**	702m^3 RC **-29%**	694m^3 Metal deck with PC **-29%**
Internal Slab Structural Volume Construction Thickness **%Savings**	4,381m^3 RC 325mm -	3,713m^3 RC 275mm **-15%**	1,535m^3 CLT 100mm **-64%**	1,529m^3 Metal deck with PC 130mm **-65%**
Roof Structural Volume Construction **%Savings**	908m^3 RC -	908m^3 RC **±0% - unchanged**	648m^3 RC **-29%**	641m^3 Metal deck with PC **-29%**
Internal Shear Wall Structural Volume Construction **%Savings**	927m^3 RC -	940m^3 RC **+1.4%**	214m^3 RC **-77%**	212m^3 RC **-77%**
Reinforcement	3.06m^3 Steel	3.07m^3 Steel	2.94m^3 Steel	2.93m^3 Steel
Total	**10,637m^3**	**9,985m^3**	**5,454m^3**	**5,377m^3**

Scenarios 2.1-2.2 – Sustainable Materials

The use of construction materials of low embodied energy and carbon and high recovery potential can significantly reduce life cycle energy and carbon [28].

Scenario 2.1 – Maximize recycled materials by replacing the 100% Ordinary Portland Cement (OPC) based concrete with a concrete mix comprising 30% pulverized fly ash, an industrial waste by-product. This would retard the concrete setting and curing time but would not reduce the long-term concrete strength [46]–[48]. Similarly, reclaimed bricks substituted red bricks within external walls. The insulation was changed to low-intensity corkboard insulation (0.04 W/mK), instead of an Extruded Polystyrene Foam board (XPS) (0.03 W/mK), ensuring a standardized thermal performance.

Scenario 2.2 – Cement stabilized earth-constructed infill elements to substitute reinforced concrete or fired brick as earth construction requires low processing energy. Such elements are appropriate as infill for multi-storey office buildings, as long as they comply with BS1377-3:1990 [49], [50]. Cement stabilized pneumatically rammed earth is a strong, durable element, also regulated in American standards under ASTM E2392/E2392M-10e1 [51]. The rammed earth wall construction, including finishing material and insulation weighs 1,543 kg/linear meter, whereas the baseline brick veneer construction weighs 944 kg/linear meter. The rammed earth solution would result in a weight increase of 61% per surface area of wall. According to the structural consultants, each concrete slab was designed to withstand a double heighted brick veneer construction. However, since each slab would only carry the weight of one storey height, the slab as designed would be able to support the rammed earth walls. Earth construction, in the form of timber internal finishes, window frames and framework, was also incorporated.

Scenarios 3.1-3.2 – Sustainable Building Systems

Scenario 3.1 - Renewables (PhotoVoltaic systems): The impact of adding an 8 kW, 50 m^2 PhotoVoltaic (PV) system with 15.4% panel efficiency was explored. The energy produced by the PV system is intended for immediate use within the analysed building with no associated battery storage or export to the grid. As IMPACT does not calculate the embodied carbon of PV systems, appropriate values from the literature were used instead. Amongst the literature analysed [52]–[56], the cradle-to-gate embodied energy data was provided by Pacca et al. [55], having the widest system boundary, covering both embodied energy and carbon data and basing its research on updated and verified databases. The specifications of polycrystalline were selected from a German-based manufacturer, therefore, factoring in additional transport to London (cradle-to-site embodied energy: 20.9 MJ/m^2; embodied carbon: 1.5 $kgCO_2/m^2$). The accumulated data is restricted to a cradle-to-site system boundary yet, according to [57], "fossil fuel use during PV system operation and decommissioning is negligible".

Scenario 3.2 - Combined Heat and Power (CHP) is an efficient building system, conjoining thermal and electric power generation from one fuel source, while reducing distribution losses. The same amount of primary fuel can, therefore, deliver more useful energy. The CHP led system used in the analysed building is composed of a CHP engine with 50kW electrical output with overall net efficiency of 90.3% and 6,000l of associated storage. Data on the embodied energy of CHP systems is scarce. Most literature sources discuss the fuel types used in CHP systems and their respective operational, rather than embodied energy and carbon [58]–[62]. Thus, embodied energy and carbon values for a domestic CHP system [63] instead of an industrial-scale system [64] were used in this study (embodied energy: 76 GJ; embodied carbon: 5.12 tCO_2), but the authors acknowledge the limitations associated with this assumption. The baseline design assumes a gas-fired heated building and an electricity-based air conditioning system for cooling.

Scenarios 4.1-4.3 – Operational energy savings

Scenario 4.1 – Temperature setpoints: An extension of thermal comfort ranges is known to significantly reduce operational loads [65]–[70]. Experimenting with heating and cooling load reductions via an additional ±2 °C flexibility on thermostat setpoints was adopted as an energy saving measure. Widened comfort ranges were validated via the Predictive Mean Vote (PMV) approach developed by Fanger [71] to investigate if they still lie within comfortable conditions under assumed office metabolic rates and seasonal clothing insulation.

Scenario 4.2 – Natural ventilation (and temperature setpoints) to supplement the previous scenario. The reliance on natural ventilation to cool the building when outdoor temperatures are between the expanded setpoints (±2°C) was allowed in order to further reduce operational loads. Scenarios 4.2.1, 4.2.2 and 4.2.3 further investigate the impact of thermal mass of different structural elements (concrete slabs, cross-laminated timber internal slabs or metal concrete decks) on additional operational energy and carbon savings, when the building is naturally ventilated. The largest internal surfaces are the slabs. The choice of materials of the first 100 mm exposed surfaces, be they heavyweight concrete (Scenario 4.2.1), timber (Scenario 4.2.2) or steel and lightweight concrete (Scenario 4.2.3), will influence the effectiveness of natural ventilation. This is to pinpoint which structural system can simultaneously result in the highest reductions in both embodied and operational loads.

Scenario 4.3 – Operation of shading elements to shield off glazed areas can reduce cooling loads in the summer. The wooden shading elements installed operate on a seasonal basis and retract in the winter via a sliding mechanism to allow for maximum solar heat gains in the colder seasons.

Scenario 5.1 – Final cumulative scenario with maximum life cycle savings

The final scenario explores the extent of savings when the most effective optimization strategies within Scenarios 1-4 were combined.

4 Results

4.1 Base case (Scenario 0.0)

Results from the original design indicate that operational carbon and energy are 6.8 and 10.5 times higher than their embodied counterpart (Figure 4), respectively, for an assumed 60 year lifespan – compliant with BS EN 15978:2011's recommendations [26]. In all impact categories, the data is both illustrated in absolute values for carbon and energy, but also in percentages of how much each element contributes to the total life cycle or the total embodied loads. Excluding operational loads, structural elements contribute the highest to embodied loads (75% of the building's embodied carbon, Figure 5). The segmentation of embodied data into building elements exposes that internal reinforced concrete slabs contribute to 34% and 43% of embodied carbon and energy, respectively (Figure 5). The second highest resource depleting building elements are reinforced concrete foundations (carbon: 18%; energy: 16%), followed by the externally insulated brick walls (carbon: 17%; energy: 11%).

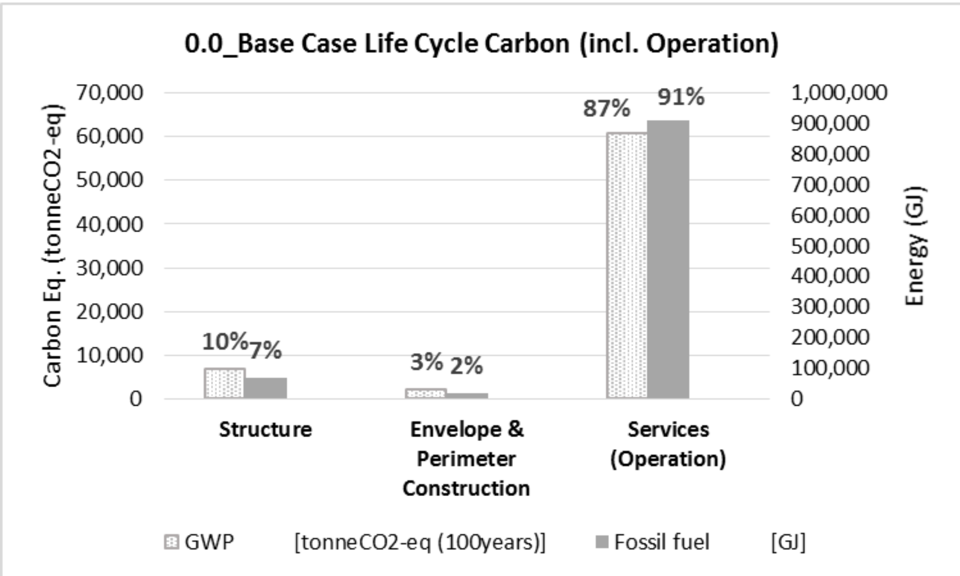
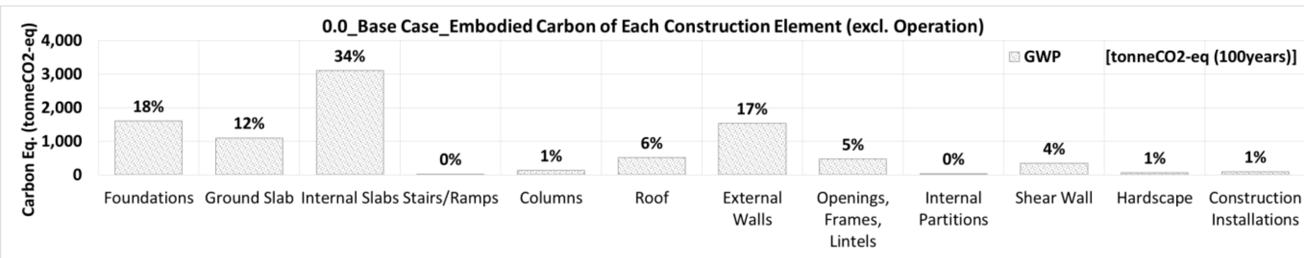


Figure 4 - Scenario 0.0: Base case, Contribution of structure, envelope and services to the total life cycle energy and carbon



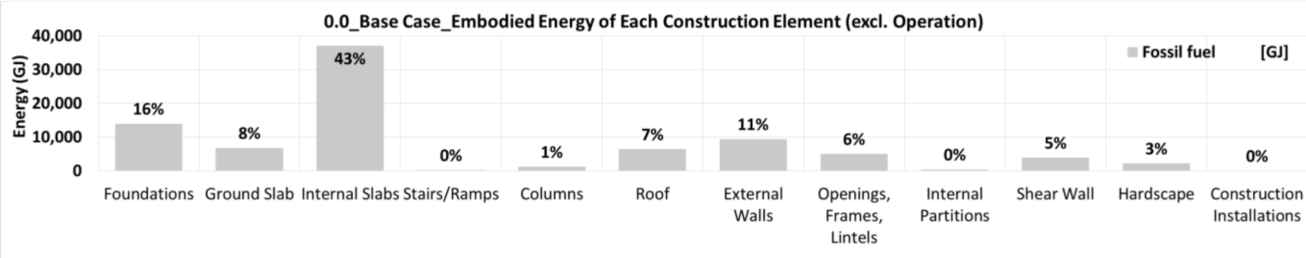


Figure 5 - Scenario 0.0: Base case: Building elements' embodied energy and carbon

Furthermore, the production stage, including extraction, processing, transport to factory, manufacturing and packaging, has the highest environmental impact within the life cycle stages (carbon: 77%; energy: 70%). Site transport and maintenance, combined, contribute to 16% to the embodied processes. Nonetheless, the transport and maintenance life cycle stages are projected to be more energy-intensive, if materials are imported. Also, the nature of office buildings might require higher refurbishment frequency with every tenancy change as reviewed in the background section [34]. Additionally, the means of disposing of the building waste beyond its lifetime end can elevate or diminish the environmental significance of the disposal stage, currently at 6% of the total life cycle.

4.2 Life cycle carbon / energy saving measures (Scenarios 1-5)

This section studies the total life cycle carbon and energy saving implications due to the simulated scenarios, while the following section dissects the data into embodied and operational savings.

The highest life cycle carbon and energy savings were observed for strategies improving the building operation (Scenarios 4). These savings were achieved by extending the thermal comfort range and applying natural ventilation (Scenario 4.2, carbon: 6.2%; energy: 5.7%), followed by the use of efficient building services, such as CHP (Scenario 3.2; Figure 7). Amongst the design solutions that target material quantity or energy intensity reductions, the use of 30% pulverized fuel ash concrete, corkboard insulation and reclaimed red bricks (Scenario 2.1) achieved the highest life cycle carbon savings (5.2%), while earth construction in the form of internal timber finishes and stabilized rammed earth walls (Scenario 2.2) achieved the highest energy savings (1.3%) relative to the base case. Carbon and energy trends are proportional, with minor exceptions. For instance, while the CLT-steel design strategy (Scenario 1.2) achieves carbon reductions of 3.1%, it does not save on life cycle energy (adds 0.6%). In line with [72], the carbon sequestration properties of the CLT-steel structure render it an appealing carbon-saving alternative. However, the combined embodied energy associated with the processing of pressurized timber panels, including the gluing materials, is higher than reinforced concrete. Scenarios that do not show high relative savings include the integration of renewables (Scenario 3.1), which is attributed to the small-scale PV system (50m^2; 8kW) adopted relative to the building size, offsetting only 0.3% of its operational energy.

4.3 Relationship between embodied energy / carbon savings and operational performance

Amongst all simulated scenarios, embodied carbon contributed to 10%-16% of operational carbon, and 10%-14% when compared to the total life cycle carbon over the building lifespan. Embodied energy had similar values of around 8%-10% of the operational loads and 7%-9% of the life cycle energy. The results are further segmented to analyse the relationship between embodied and operational savings (Figure 8; Figure 9). Strategies addressing operational reductions, with the exception of PV integration, achieve larger savings than those aiming to optimize building materials.

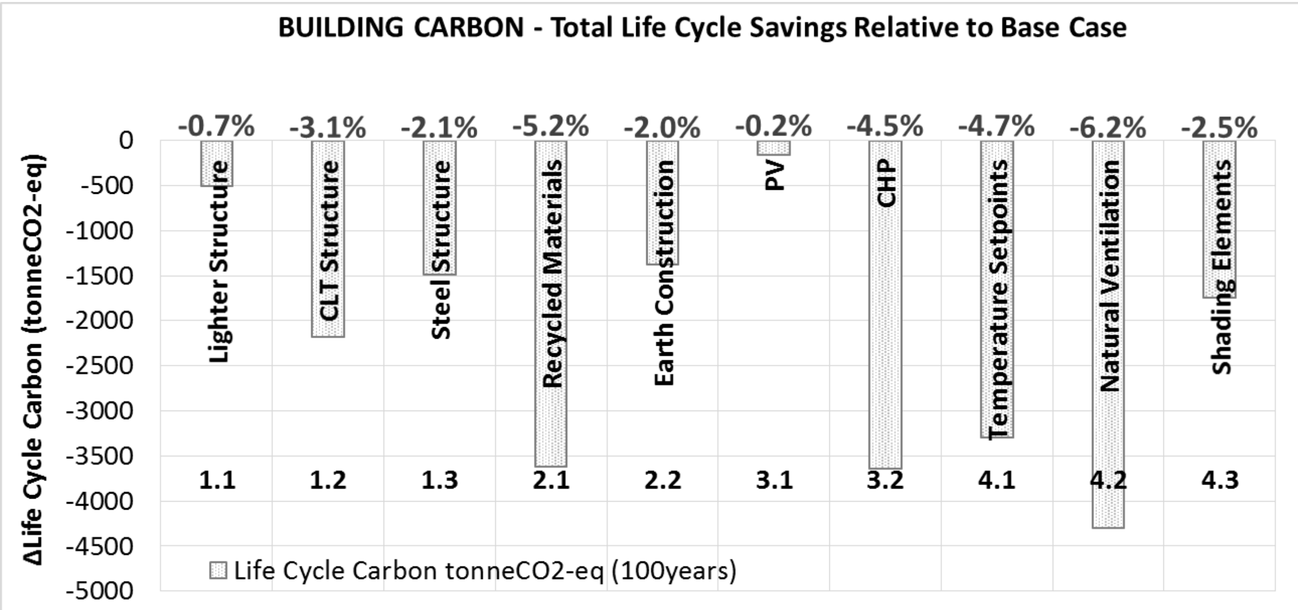


Figure 6 - Impact of design optimizations on total life cycle carbon savings relative to the original design

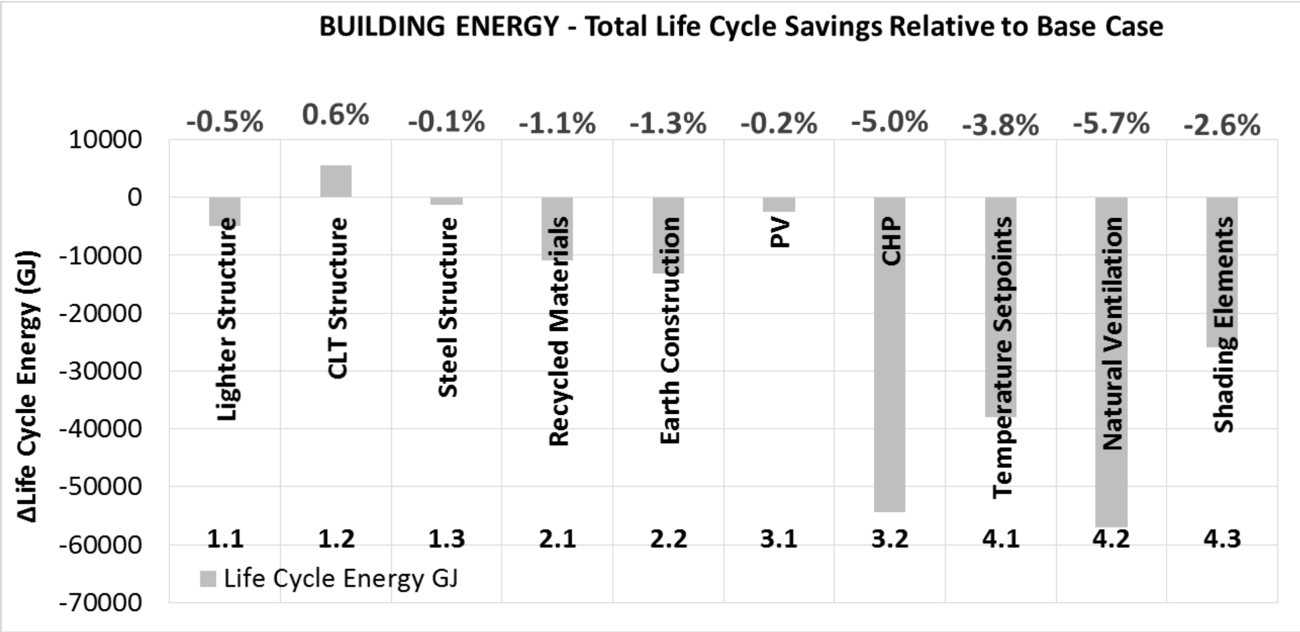


Figure 7 - Impact of design optimizations on total life cycle energy savings relative to the original design

In comparison, the highest achieved embodied carbon savings (recycled materials, Scenario 2.1) are roughly 70% of the highest operational reductions (Natural Ventilation, Scenario 4.2). The relative importance of embodied energy savings is lower, as the maximum energy savings contribute only to 20% of the highest operational savings within the same scenarios (Figure 9).

While this implies that operational saving measures are more significant compared to embodied ones on the assumed 60 year building life, the implementation of embodied strategies proves significantly easier at early design stages. Operational strategies are susceptible to variations in thermal comfort predictions (Scenarios 4.1 - 4.2) that may not match occupant thermal expectations. Additional uncertainty is associated with the magnitude of operational savings, when grid decarbonisation and climate change are factored in. With the increase in temperatures in a heating dominated climate, lower operational loads may be applicable. Similarly, with a future power supply that is less dependent on carbon, the environmental impact of the building's operation may prove less significant. It is also important to consider the magnitude of the "year 0" initial environmental savings that can be easily achieved with the implementation of some of these strategies.

Finally, even though all envelope- and structural-based energy conservation measures have a standardized thermal performance, expressed as a steady-state U-Value, the dynamic thermal simulation models result in slight changes to operational carbon and energy. The reason is that the conductivity of a material varies with changing outdoor and indoor conditions and that materials absorb and release heat at different rates. With a consistent Gross Internal Floor Area (GIFA), the materials with lower heat storage capacity (Scenarios 1.2 – 1.3) show slightly higher increases in operational energy as they are less able to act as passive heat sinks or heat sources. Annual heating energy increases by up to 15% for the most lightweight structure, but the heating end use only contributes to 9% of the total annual operational energy consumption.

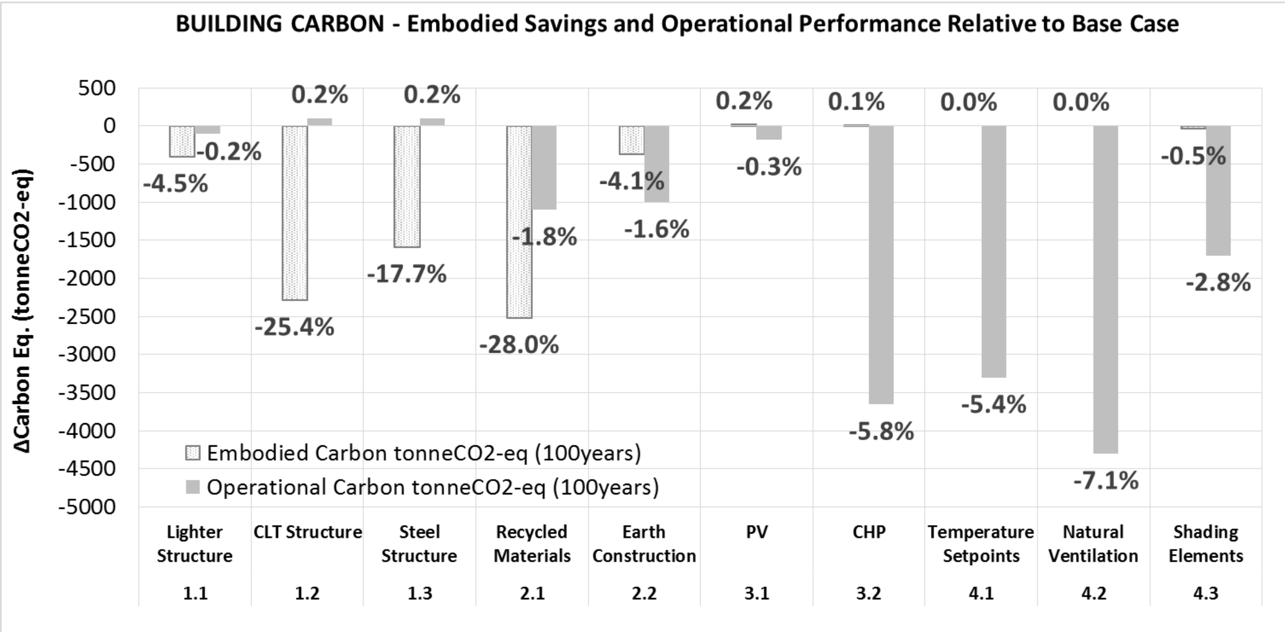


Figure 8 - Comparison of embodied versus operational carbon savings relative to the base case

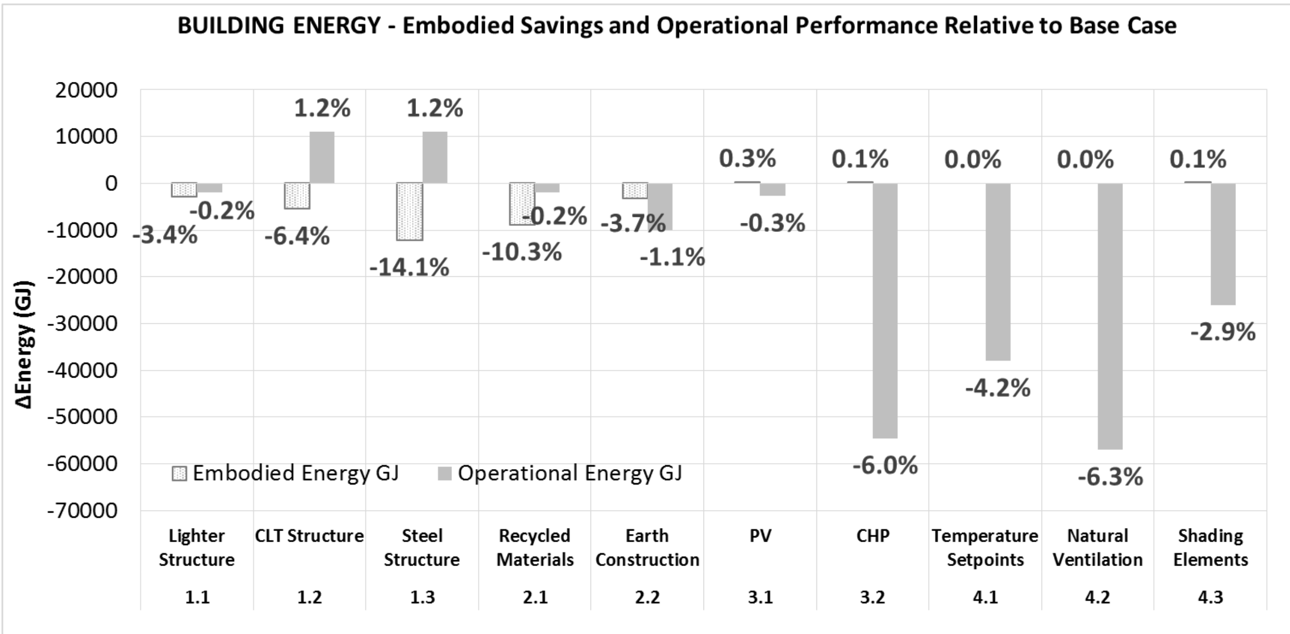


Figure 9 - Comparison of embodied versus operational energy savings relative to the base case

4.4 Impact of thermal mass on effectiveness of natural ventilation

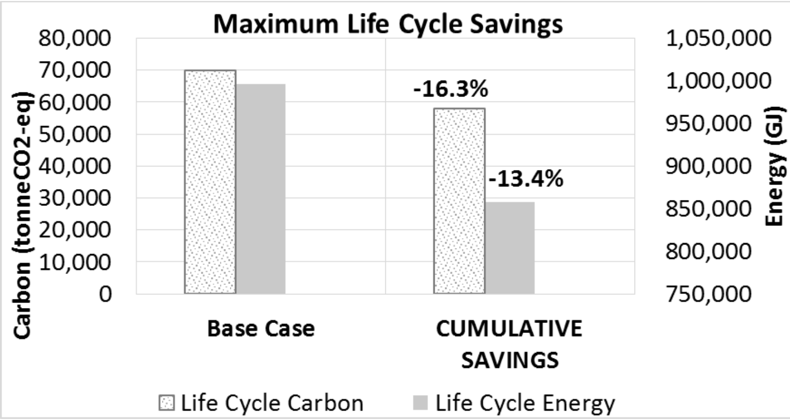
Scenarios 4.2.1, 4.2.2 and 4.2.3 further investigate the impact of thermal mass of different exposed structural elements on additional operational loads, when the building is naturally ventilated. Table 5 outlines the main differences of each structural element, highlighting that reinforced concrete structure has the highest thermal mass, followed by the lightweight concrete metal deck and the dense CLT structure. The base Scenario 4.2 already saved 6.3% and 7.1% on operational energy and carbon, respectively. Since windows only open when outside temperatures are within the comfort range (18-26°C), it is observed that the internal slabs with higher thermal mass preserve comfortable temperatures longer once the windows are closed. With a higher thermal mass factor, a slower building response is observed, resulting in lower operational loads (Table 5). Nonetheless, the percentage difference to the most heavyweight structure (Scenario 4.2) is only a maximum of +1.1% for annual operational energy. This does not indicate that the material properties have little impact on the effectiveness of natural ventilation, seeing as the strategy in place does not exploit outdoor conditions to the fullest capacity, i.e. night ventilation etc. Natural ventilation only takes place when outdoor conditions lie within comfort temperatures. As the building is operating on a mixed-mode basis, this type of strategy was deemed most fitting to the real-life use of the building.

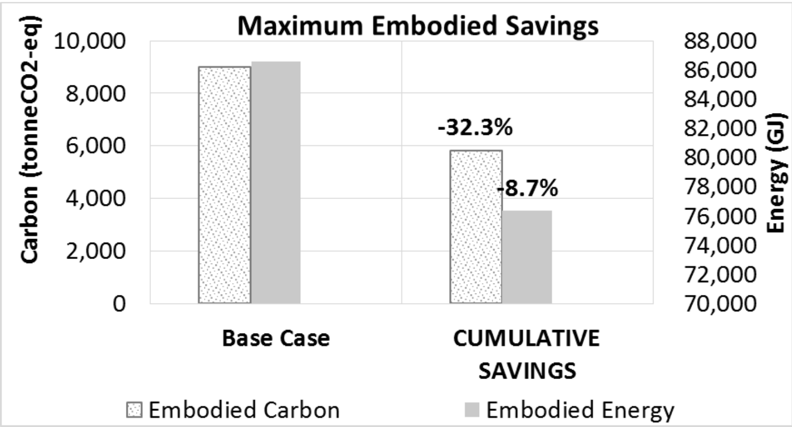
Table 5 - Impact of thermal mass on effective of natural ventilation

Parameters	**Unit**	**4.2 Natural Ventilation w/ Base Case Structure**	**4.2.1 Lighter Structure and Natural Ventilation**	**4.2.2 CLT Structure and Natural Ventilation**	**4.2.3 Metal Deck and Natural Ventilation**
Description of structure	-	**Medium weight** reinforced concrete columns and flat slab construction	**Medium weight** 10% lighter RC structure	**Very Lightweight** CLT and steel columns/beams	**Very Lightweight** metal deck with infill concrete slabs and steel columns/beams
Density	kg/m^3	2400	2400	470	2400
Structural thickness	mm	325	275	100	130
Thermal mass factor	kJ/m^{2}K	202	202	58	78
Natural Ventilation		**Most Effective**	**Effective**	**Least Effective**	
%Savings in Energy relative to Scenario 4.2			**± 0.0%**	**+ 1.1%**	**+ 0.8%**

4.5 Maximum cumulative savings (Scenario 5.1)

Maximum life cycle savings amount to 16.3% on carbon and 13.4% on energy, with savings of 32.3% on embodied carbon and 8.7% on embodied energy achieved (Figure 10). The operational carbon and energy savings are reduced by roughly 14% on both indicators. Design solutions that lead to the maximum savings are extracted from a series of combined scenarios (Table 6).





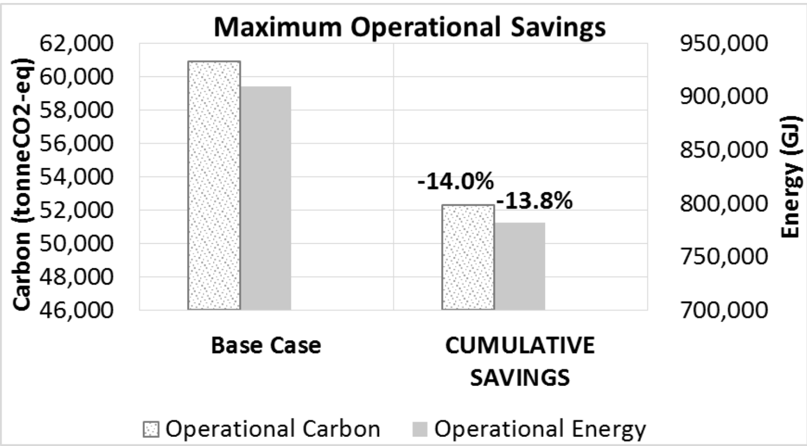


Figure 10 – Scenario 5.1: Highest life cycle, embodied and operational energy/carbon savings relative to Scenario 0.0

Table 6 – Scenario 5.1: Reasons for combining different saving measures for highest savings

Adopted Scenario	Affected Building Elements	Main Features	Reason for Choosing Scenario
Scenario 1.1	All structural elements	- Lighter structure (10% savings)	- High structural savings, easily combined with Scenario 2.1 (highest embodied savings) - Cost savings and higher material savings - Durable construction
Scenario 2.1 – Recycled materials	All building elements with a concrete, brick or insulation component	- Recycled RC content (30% PFA) - Corkboard insulation, instead of XPS -Reclaimed brick walls	- Savings up to 28% and 10% on embodied carbon and energy - Adoption of a waste product, turned into a resource - Easily integrated into all building elements

Scenario 2.2 – Earth construction	Internal partitions and window frames) – no adoption of rammed earth walls	- Timber finishes, instead of plasterboard and aluminium frames	- Respects space efficiency - High carbon capture properties (timber) - No added labour intensity
Scenarios 3.2 and 3.3 – PV and CHP	Building services	- 50m^2 PV installation - CHP replacing normal gas boilers	- High life cycle savings - Cuts down on annual energy bills - Efficient use of environmental resources
Scenario 4.2	Building operational systems	- Expanding thermal comfort conditions	- Highest life cycle savings - Extended temperature setpoints combined with natural ventilation require no resources for implementation (highest operational savings: 6%)
Scenario 4.3	Shading elements (added)	- Wooden louvers to reduce cooling loads (seasonal application)	- Provide higher envelope performance - Composed of timber, a renewable material that offsets carbon emissions in its initial life cycle

Both studied environmental indicators are not consistently proportional in magnitude, as some scenarios use lower carbon emitting solutions that are energy intensive to realize. Translated into life cycle stages, the final proposed design saves 40% embodied carbon on production, 22% on construction and 35% on disposal. Within a 60 year assumed building lifetime, embodied energy and carbon are the equivalent of 5.8 and 4.3 years of operational energy and carbon, respectively (Scenario 5.1). The base case has comparatively higher payback times of 8.2 and 4.6 years for carbon and energy, respectively, indicating higher embodied loads.

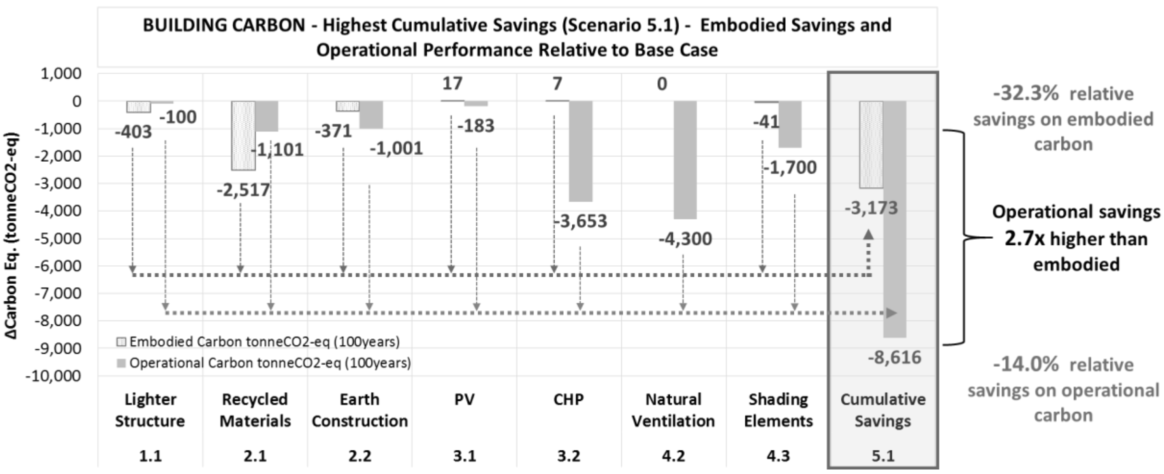


Figure 11 - Impact of distinct scenarios on the maximum cumulative savings (Scenario 5.1) on embodied and operational energy

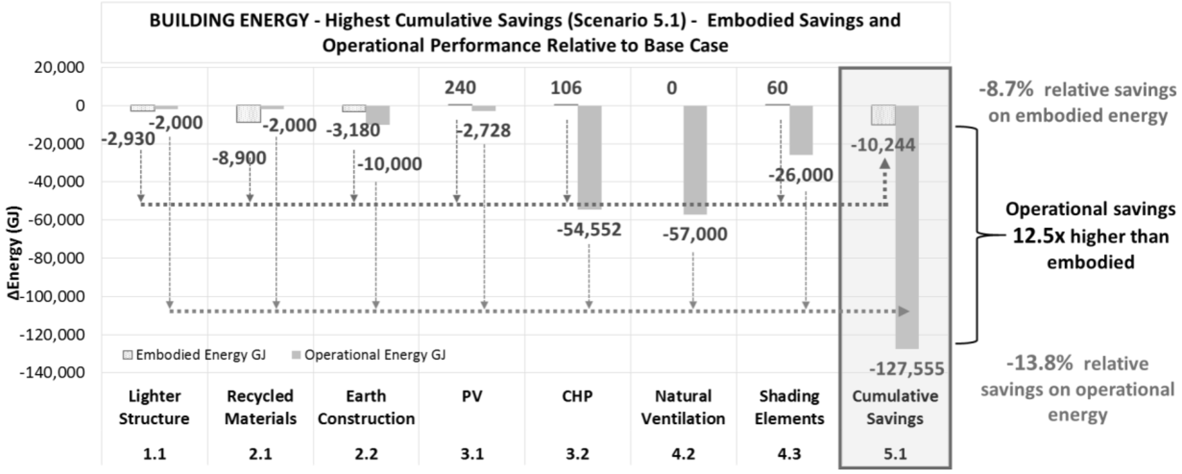


Figure 12 - Impact of distinct scenarios on the maximum cumulative savings (Scenario 5.1) on embodied and operational energy

5 Discussion

5.1 Interactions between embodied and operational processes

Findings reveal that a balance between optimization strategies that focus on reducing materials' quantity versus reducing their energy intensity need to be met in order to maximize life cycle savings. The highest embodied carbon savings were attained by cutting down on energy intensities of construction materials (Scenario 2.1). Yet, integrating higher-intensity structural materials, whose technical performance allowed for significant quantity cuts (40%), proved second-most effective (Scenarios 1.2 - 1.3) for the assumed building lifetime. Energy intensity strategies only proved significant, if applicable to the majority of building elements. For instance, though earth construction (Scenario 2.2) considerably reduced the element-level environmental impacts within walls, its lower durability limits its applicability to all building elements, e.g. to structural elements.

Interestingly, life cycle regulations, such as the CfSH&CT:2012 [73] advocate for sector-level emissions reductions, outlining responsibilities of project stakeholders, with little emphasis on efficient material quantity-saving designs. No restrictions on elaborate cladding quantities or unnecessary structural additions to construction thicknesses exist. Designers and consultants should, thus, simultaneously strive to combine both strategies. The highest operational savings were achieved through increasing awareness of adaptive user control over their environment (Scenario 4.2), or through the integration of efficient building services, e.g. CHP (Scenario 3.2). Predictions of operational savings that are driven by occupant behavioural trends might not be accurate.

Comparatively, this enables strategies targeting embodied processes to be more easily addressed because they are not dependent upon human behaviour.

5.2 Feasibility of Realizing Proposed Solutions

While some strategies indicated life cycle carbon and energy savings relative to the baseline, the feasibility of implementation might restrict their appeal as optimized design solutions (Table 7).

Table 7 - Feasibility of proposed solutions

Element	Implementation aspects affecting potential for life cycle energy/carbon savings
Structure	
1.1-Lighter Structure	• Might reduce flexibility for future adaptation, e.g. change in use
1.2-CLT-Steel Structure	• Innovative design subject to lengthy planning approval procedures • High pressure gluing process might be energy-intensive • Lower thermal mass – reducing thermal storage for chilled ceilings • Additional fire protection required
1.3-Metal Deck-Steel Structure	• Maintenance required every 25 years • Higher perceived vibration relative to reinforced concrete solution • Lower thermal mass – reducing thermal storage for chilled ceilings (while adding ceiling-hung concrete panels can increase thermal storage, the building weight will increase, affecting foundations) • Additional fire protection required
Sustainable Materials	
2.1-Recycled Materials	• Space inefficiency due to thicker wall construction • Secure supply of waste by-products or recycled materials • 30% PFA concrete requires longer time to set and cure which may impact the construction schedule • Could be processed abroad (resulting in higher life cycle emissions within transport and product stage). The UK outsources significant quantities of its construction materials, with imports making up more than 1.2 times the size of the domestic production [74].
2.2-Earth Construction	• Space inefficiency due to thicker constructions (i.e. rammed earth walls) • Technical performance – strength; weathering, durability issues • Potentially more labour intensive on-site • Needs additional cladding to protect walls from heavy rainfall
Sustainable Building Systems	
3.1-PV	• Capital cost versus payback time considerations • Energy storage (batteries – if any) need to be replaced every 5 years
3.2-CHP	• Higher capital cost (compared to regular boilers) • Higher maintenance cost • Matching heat and electricity demands
Operational Strategies	
4.1/4.2-Temp. Set-points and Natural Ventilation	• Risk of system failure and not being able to meet peak loads as a result of lower system sizing, if occupancy's thermal expectations do not match design
4.3-Shading Elements	• Higher capital cost • If not sensor-operated, their use might not output the same magnitude of savings predicted • Increase heating loads, if not designed for seasonal flexibility
Maximum Savings	
5.1 Final Cumulative Savings	• Budget concerns with associated higher building costs due to added elements of CHP, PV and shading elements

5.3 Addressing Relevant Findings: Critique and Replicability of Methods

This discussion contextualizes the applicability of this study to other office buildings. As a case study, conclusions should not be generalized directly to other offices, as specifications of life cycle saving measures may vary. Nonetheless, the systematic methodology adopted is transferrable, where the examination of a “palette” of optimization strategies can achieve the highest environmental savings. Existing early-stage LCA studies [19], [21]–[23], [25], [27] primarily focus on residential structures. This study combines both embodied and operational saving strategies. In agreement with [75], slabs, foundations and walls contribute the highest to life cycle impacts. Similarly, the study at hand concludes that quantity savings are slightly less effective than material intensity savings, though they should be combined. It reveals that building element volume savings, resulting from using materials with higher technical performance, do not achieve the highest environmental savings. On the contrary, [19] recommends prioritizing the reduction of construction thicknesses, i.e. material quantities. However, both conclusions cannot be compared, as [19] compares minimal input parameters without accounting for innovative materials, such as reclaimed brick, recycled concrete or CLT. Additionally, it is not specified, whether material volumes were reduced, when changing constructions. Lastly, the study is in line with [27] that suggested the operational stage contributed to 90% and 95% of the entire life cycle for the retrofit versus new build option, respectively. Operational carbon contributed to 86% of the total life cycle energy in all strategies that focused on reducing operational systems only and increased up to 90% for strategies that focused on reducing the embodied load of the building. The findings indicate the dominant contribution of the operational load of the building, while a slight reduction in its significance can take place, if the building’s embodied load is not optimized.

5.4 Study and Tool Limitations

Building elements’ limitations associated with this study are that the embodied data of building services are excluded [76], while only their operational intensity is accounted for due to limited data availability. Also, the data representativeness of transport energy embedded within software and the manual data extracted for PV, CHP systems and demolition energy might not match reality. Predictions of the magnitude of operational saving strategies might not match reality, if actual occupant thermal comfort ranges are discrepant. All the aforementioned limitations are intrinsic to initial project stages. This study is case-specific in its design recommendation, albeit with a prototypical methodology. Since an identification of building components and respective materials with the highest life cycle environmental impacts has taken place, these should be consistently examined throughout the project’s design and construction phases. Broader aims addressed in the

Introduction can only be met, if more LCA studies highlight the importance of carbon and energy savings due to various optimization strategies, while investigating the ratio of embodied versus operational loads for office buildings in the UK.

Life cycle study parameter limitations include that the cradle-to-grave study does not include elements' recovery potential (cradle-to-cradle) and that the environmental savings are not complemented by their financial feasibility, which would indicate the viability of implementing the recommended solutions. Similarly, the studied environmental indicators might not be representative of the holistic building's environmental impact. Other indicators, e.g. human toxicity, water extraction and waste generation [26], may alter final design decisions. The recommendation is to integrate LCA within the entire design process and prioritize budgeting of suggested design modifications. As IMPACT outputs all 13 indicators, the extraction of this already available data can form the basis of another research.

Furthermore, uncertainty associated with the magnitude of operational savings may be present, as the software does not factor in both grid decarbonisation and climate change impacts.

6 Conclusions

The impact of distinct design philosophies to reduce original life cycle loads at an early stage, at which modifications are flexible, was quantified for a case study office building in London, UK. Investigations to structure, envelope, building systems and operational facility management provided basis to an all-encompassing design recommendation. The savings were achieved via integrating the most effective measures: adopting natural ventilation, expanding on thermostat settings, adopting CHP and PV systems, re-designing a 10% lighter reinforced concrete structure with 30% pulverized fly ash and using reclaimed brick, low intensity corkboard insulation and timber-based internal finishes. It was found that early-stage LCA proves significant: On the building level, design modifications saved 16.3% for life cycle carbon and 13.4% on life cycle energy, with 32.3% and 8.7% savings on embodied carbon and energy, respectively. The methodological framework is also easily replicable. The use of one BIM software to estimate one's operational loads, compliance with UK building regulations and life cycle environmental impact ensures a swift integration of LCA within early-design stages, unlike most studies that rely on a minimum of two LCA tools [19]. Future research should highlight other environmental indicators, as water, waste and human toxicity, to verify that their impact does not alter design decisions. With regards to the incomplete and unstandardized nature of LCA, both the development of embodied data for building services is vital and the standardization of a holistic calculation approach are to be prioritized. Similarly, as suggested by Ariyaratnea and Moncaster [77], there is no stakeholder, officially liable for reducing the building's environmental footprint and sustainability consultants are not always involved at early stages. If sufficiently detailed data provided from architects, structural and MEP consultants is unavailable, such interlocking design optimization strategies, easily facilitated by BIM, will be fragmented. The process of combining all fields to perform feasible comprehensive LCA on office buildings should be further investigated.

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7 Appendix

7.1 Statistical Analysis Detailed Findings

Notice that different academic articles are found to express embodied energy significance in three different ways (Total Embodied Energy, %Embodied vs. Operational Energy or %Embodied vs. Total Life Cycle Energy), leaving some columns empty.

Table 8 - Statistical Analysis Performed on Literature Findings: Significance of Embodied Energy (summarized in p.530)

Summary of Literature Findings	Embodied Energy [GJ/m2]	%Embodied versus Operational Energy	%Embodied versus Total Life Cycle Energy
All 81 sources (112 data points)			
Mean	**8.2**	**34%**	**24%**
stdev	6.1	57%	20%
Maximum	30.9	400%	100%
Minimum	1.5	5%	2%
95% Confidence Interval	1.1	11%	
Residential			
Mean	**7.1**	**23%**	**22%**
stdev	6.0	21%	18%
Maximum	30.9	100%	69%
Minimum	1.5	3%	3%
95% Confidence Interval	1.5	5%	
Commercial			
	10.0	**25%**	**26%**
stdev	5.9	7%	15%
Maximum	27.0	38%	67%
Minimum	3.4	15%	13%
95% Confidence Interval	1.8	2%	
UK (Residential/Commercial)			
Mean	**-**	**-**	**41%**
Stdev	-	-	25%
Maximum	-	-	80%
Minimum	-	-	3%
95% Confidence Interval	-	-	
Excluded Study[7] [29]			
Mean	**40-50**	**173-227%**	**63-69%**

Table 9 - Data gathered from Literature regarding the Significance of Embodied Energy

Author	**Location**	**Building Function**	**Life Span (years)**	**Total Embodied Energy (GJ/m²)**	**%Embodied vs. Operational Energy**	**%Embodied vs. Total LC Energy**
Hill – quoted in [8]		Residential		3.6		
Edwards et al. – qtd. [8]		Residential		3.9		
D' Cruz – qtd. [8]		Residential		4.3		
				5.3		
Pullen – qtd. [8]		Residential		4.9		
Lawson – qtd. [8]		Residential		5		
Pullen – qtd. [8]		Residential		5.9		
Ballantyne et al. – qtd. [8]		Residential		6.6		
Treloar – qtd. [8]		Residential		6.8		

[7] One data point is excluded for extending its LCA to a city-level by adding occupant transportation from and to the site. While transportation sustainability is crucial to a building's functioning and is awarded by BREEAM and LEED [52][53], a fair comparison between all studies cannot be otherwise established.

Treloar – qtd. [8]		Residential		8.76		
Honey and Buchanan – qtd. [8]		Commercial		3.4		
				6.5		
Cole and Kernan – qtd. [8]		Commercial		4.3		
				5.1		
Oppenheim and Treloar – qtd. [8]		Commercial		5.5		
Oka et al. – qtd. [8]		Commercial		8		
				12		
Tucker and Treloar – qtd. [8]		Commercial		8.2		
Yohanis and Norton – qtd. [8]		Commercial		10.5		
Stein et al. – qtd. [8]		Commercial		18.6		
Tucker et al. – qtd. [8]		Commercial		19		
CSIRO – qtd. [8]	Australia				25%	20%
						25%
Crawford and Teloar – qtd. [8]	Australia				33-66%	50%
Lee and White – qtd. [1]	UK		100			3%
						35%
Yohanis and Norton – qtd. [1]	UK		25			67%
Eaton and Armaton – qtd. [1]	UK		60			37%
						43%
Smith – qtd. [1]	UK		NA			80%
CIBSE – qtd. [1]	UK		60			42%
						68%
Engin and Francis – qtd. [1]	USA; Canada		60			11%
						50%
Webster – qtd. [1]	USA; Canada		50			2%
						22%
Athena – qtd. [1]	USA; Canada		60			9%
						12%
Build Carbon Neutral – qtd. [1]	USA; Canada		66			13%
						18%
CSIRO – qtd. [1]	Australia		100			10%
Thomark – qtd. [1]	Sweden		50			45%
Ramesh et al. [9]			60			10%
			60			20%
Aldalberth – qtd. [9]	Sweden	Residential	50	6.912	10%	9%
			50	7.128	10%	10%
			50	7.128	11%	10%
			50	7.128	10%	10%
			50	7.344	11%	11%
			50	7.128	11%	10%
			50	7.128	10%	10%
			50	7.128	12%	11%
			50	5.4	11%	10%
			50	5.616	10%	9%
			50	7.128	10%	10%
			50	5.184	9%	8%
Citherlet and Defaux – qtd. [9]	Switzerland	Residential	50	5.832	14%	13%
			50	6.696	21%	17%
			50	5.4	29%	23%
Fay et al. – qtd. [9]	Australia	Residential	100	21.816	38%	28%
			100	21.168	34%	25%
Junnila et al. – qtd. [9]	USA; Europe	Commercial	50	8.64	15%	13%

			50	15.768	19%	16%
Mithratatne and Vale – qtd. [9]	New Zealand	Residential	100	2.592	52%	26%
			100	2.808	62%	29%
			100	3.024	117%	42%
Sartori and Hestenes – qtd. [9]	Germany	Residential	80	4.104	7%	7%
			80	4.32	10%	9%
			80	4.32	14%	12%
			80	6.264	45%	31%
			80	23.112		100%
			80	4.752	45%	31%
Shukla et al. – qtd. [9]	India	Residential	40	7.992	154%	61%
Suzuki and Oka – qtd. [9]	Japan	Commercial	40	12.096	18%	15%
			40	14.904	23%	19%
			40	14.904	29%	23%
			40	17.928	29%	23%
			40	23.976	33%	25%
			40	17.928	19%	16%
			40	27	38%	28%
Thomark – qtd. [9]	Sweden	Residential	50	8.424	33%	27%
Treloar et al. – qtd. [9]	Australia	Residential	30	30.888	61%	38%
Utama and Gheewala – qtd. [9]	Indonesia	Residential	40	2.808	15%	13%
			40	1.512	7%	7%
Winther and Hestnes – qtd. [9]	Norway	Residential	50	3.024	9%	8%
			50	2.808	11%	10%
			50	2.592	9%	8%
			50	1.944	5%	5%
			50	5.4	38%	28%
Zimmermann et al. – qtd. [9]	Switzerland	Residential	50	4.32	6%	6%
			50	6.048	9%	8%
Raymond et al. [34]				4		
				12		
Stein et al. – qtd. [34]	USA	Commercial		18.6		
Gardiner and Theobald– qtd. [34]	UK	Commercial				
Oka et al. – qtd. [34]	Japan	Commercial		12.06		
				10.09		
				11.18		
				11.87		
				10.53		
				8.03		
Tucker and Treloar– qtd. [34]	Australia	Commercial		8.23		
Honey and Buchanan – qtd. [34]	New Zealand	Commercial		6.46		
				7.75		
				4.75		
				3.35		
Buchanan and Honey – qtd. [34]	New Zealand	Commercial		3.7		
				6.6		
				5.6		
Raymond et al. qtd. [34]	Canada	Commercial		4.54		
				5.13		
				4.79		
				4.27		

				4.85		
				4.51		
Treloar et al. – qtd. [28]		Office		10.7		
Vukotic and Fenner – qtd. [28]		current consensus			25%	20%
		future predictions			67%	40%
Cabeza et al. [78]		any	50	2.37	25%	
		future buildings with low operations			400%	
Stephan et al. [36]				2.5		
				4.5		
				12		
				15		
		residential (passive)	50	25.82727	144%	59%
		residential (passive)	50	40.68182	227%	69%
		residential (passive)	50	23.40067	81%	45%
		residential (passive)	50	50.10101	173%	63%
		conventional buildings				2%
						38%
		low energy buildings				9%
						46%
Huberman and Pearlmutter – qtd. [15]	Palestine		50			60%
Plank – qtd. [15]	UK					10%
Reddy and Jagadish [79]				4.21		
				2.92		
				1.61		

7.2 Inputs for Scenario 0.0 - Base Case

Table 10 - Scenario 0.0_Base Case Inputs and Assumptions in detail

	Building Element – 0.0 Base Case	Material Quantities	Construction (exterior to interior layers)	U-Value (W/m²K)
Structural Elements	**Foundation** (**Deep Piles**) Structural Volume	**1,950m³**	Concrete: RC35 Steel reinforcement: 2.10%	-
	Contiguous Piles Structural Volume	**448m³** The addition of deep and contiguous piles is 2,398m³ as per Structural designers	Concrete: RC35 Steel reinforcement: 2.10%	-
	Pile Caps Structural Volume	**698m³** Equals to structural foundations	Concrete: RC35 Steel reinforcement: 2.10%	-
	Column Structural Volume Column Spacing (Grid)	**224m³** 9m x 9m	Concrete: RC35 Steel reinforcement: 3.25%	-
	Beams/Structural Framing Structural Volume	**None** (flat slab construction)	-	-
	Lintels Structural Volume	**71m³**	Concrete: RC35 Steel reinforcement: 2.10%	-
	Stairs Structural Volume	**45m³**	Concrete: RC35 Steel reinforcement: 3.25%	-
	Basement Slab Structural Volume	**982m³**	190mm Rigid sheet insulation (XPS) 400mm Composite: RC35 (2.10% steel reinforcement)	0.1228

			20mm Chipboard sheet	
	Internal Slab Structural Volume	**4,381m³**	50mm Carpet tiles 325mm Composite: : RC35 (2.10% steel reinforcement)	0.1620
	Roof Structural Volume	**908m³** The addition of all slabs and roof = floors 6,271m³ as per Structural designers	2.5mm Roof membrane (bituminous) 0.3mm Vapour control layer 1mm Roof deck 270mm Corkboard insulation 400mm Composite: : RC35 (2.10% steel reinforcement)	0.1234
	Internal Shear Wall Structural Volume	**927m³**	12mm Plasterboard sheet 70mm Steel framework 160mm Composite: Block concrete, mortar and steel reinforcement (2.10%)	1.694
Non-Structural Elements	**External Walls** Thickness Total Volume	**0.275m** 1215m³	100mm Composite: Brick and Mortar 140mm Rigid sheet insulation (XPS) 15mm Particleboard general sheet 5mm Adhesive for plasterboard 15mm Plasterboard sheet	0.1810
	External Walls (Basement) Thickness Total Volume	**0.410m** 318m³	125mm Rigid sheet insulation (XPS) 250mm Composite: : RC35 (2.10% steel reinforcement) 15mm Particleboard general sheet 5mm Adhesive for plasterboard 15mm Plasterboard sheet	0.1866
	Internal Partitions Thickness	**0.100m**	12mm Plasterboard sheet 75mm Steel framework 12mm Plasterboard sheet	1.7809
	Windows with Frames Thickness Total Surface Area	**0.360m** 2,975m²	20% Aluminium window frame 18mm Outer glazing pane 12mm air-filled cavity 6mm Inner glazing pane	1.4467
	Hardscape Total Surface Area	1,778m²	75mm Asphalt paving over prepared sub-base	-

*Lintels' and stairs' volumes have been deduced from the plans, as they were not part of the original structural calculation

7.3 Inputs for Scenarios 1.1-1.3 - Structural Changes

Highlighting changes from Scenario 0.0: Base Case only

Table 11 - Scenario 1.1_Lighter Structure Inputs and Assumptions in detail[8]

Building Element – 1.1 Lighter Structure		Material Quantities	Construction (exterior to interior layers)	U-Value (W/m²K)
	Column Structural Volume Column Spacing (Grid)	**227m³** 9m x 9m	Concrete: RC35 Steel reinforcement: 3.25%	-
	Internal Slab Structural Volume	**3,713m³**	50mm Carpet tiles 275mm Composite: : RC35 (2.10% steel reinforcement)	0.1673
	Internal Shear Wall Structural Volume	**940m³**	12mm Plasterboard sheet 70mm Steel framework 162mm Composite: Block concrete, mortar and steel reinforcement (2.10%)	1.694

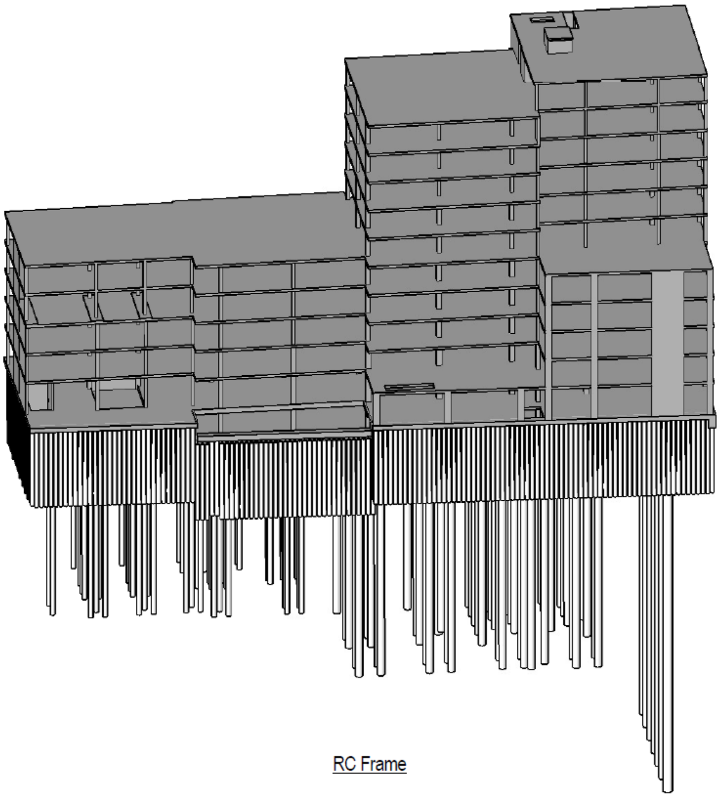
[8] All unchanged elements can be extracted from the base case

Table 12 - Scenario 1.2_CLT and Steel Frame Inputs and Assumptions in detail

Building Element – 1.2 CLT and Steel Frame		Material Quantities	Construction (exterior to interior layers)	U-Value (W/m²K)
Structural Elements	**Foundation (Deep Piles)** Structural Volume	 **1,429m³**	Concrete: RC35 Steel reinforcement: 2.10%	-
	Contiguous Piles Structural Volume	 **329m³**	Concrete: RC35 Steel reinforcement: 2.10%	-
	Pile Caps Structural Volume	 **342m³**	Concrete: RC35 Steel reinforcement: 2.10%	-
	Column Structural Volume Column Spacing (Grid)	 **29m³** 9m x 9m	Galvanized steel (hot rolled)	-
	Beams/Structural Framing Structural Volume	 **107m³**	Galvanized steel (hot rolled)	-
	Basement Slab Structural Volume	 **702m³**	190mm Rigid sheet insulation (XPS) 280mm Composite: RC35 (2.10% steel reinforcement) 20mm Chipboard sheet	0.1228
	Internal Slab Structural Volume	 **1,535m³**	50mm Carpet tiles 100mm: High Pressure Cross Laminated Timber with 470kg/m³ density	0.1676
	Roof Structural Volume	 **648m³** The addition of basement slab and roof sums up cast in situ concrete floors = 1,349m³	2.5mm Roof membrane (bituminous) 0.3mm Vapour control layer 1mm Roof deck 272mm Corkboard insulation 280mm Composite: : RC35 (2.10% steel reinforcement)	0.1234

Table 13 - Scenario 1.3_Metal Deck and Steel Frame Inputs and Assumptions in detail

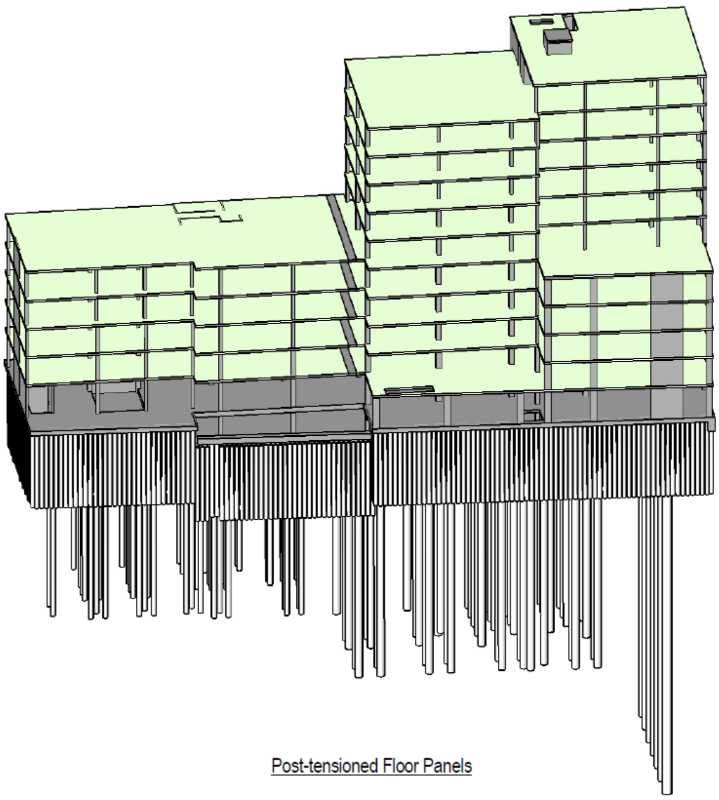
Building Element – 1.3 Metal Deck and Steel Frame		Material Quantities	Construction (exterior to interior layers)	U-Value (W/m²K)
Structural Elements	**Foundation (Deep Piles)** Structural Volume	 **1,475m³**	Concrete: RC35 Steel reinforcement: 2.10%	-
	Contiguous Piles Structural Volume	 **339m³**	Concrete: RC35 Steel reinforcement: 2.10%	-
	Pile Caps Structural Volume	 **303m³**	Concrete: RC35 Steel reinforcement: 2.10%	-
	Column Structural Volume Column Spacing (Grid)	 **33m³** 9m x 9m	Galvanized steel (hot rolled)	-
	Beams/Structural Framing Structural Volume	 **77m³**	Galvanized Steel (hot rolled)	-
	Basement Slab Structural Volume	 **694m³**	190mm Rigid sheet insulation (XPS) 280mm Composite: RC35 (2.10% steel reinforcement) 20mm Chipboard sheet	0.1227
	Internal Slab Structural Volume	 **1,529m³**	50mm Carpet tiles 130mm Plain lightweight concrete 1.3mm Corrugated sheet metal deck	0.1632
	Roof Structural Volume	 **641m³** The addition of basement slab and roof sums up cast in situ concrete floors = 1,335m³	2.5mm Roof membrane (bituminous) 0.3mm Vapour control layer 1mm Roof deck 270mm Corkboard insulation 280mm Composite: : RC35 (2.10% steel reinforcement)	0.1236



- 325mm thk RC flat slab
- No downstand beams required
- Stability provided through shear walls
- Roughly same number of piles as PT option

Material	Category	Total Volume	Material Density	Weight (kG)
Concrete - Cast In Situ				
Concrete - Cast In Situ	Floors	6271.95 m^3	2500	15679867.531
Concrete - Cast In Situ	Structural Columns	224.44 m^3	2500	561090.905
Concrete - Cast In Situ	Structural Foundations	698.33 m^3	2500	1745837.323
Concrete - Cast In Situ	Walls	926.72 m^3	2500	2316808.573
Concrete - RC Pile				
Concrete - RC Pile	Structural Foundations	2397.55 m^3	2500	5993876.900
Metal - Steel - General				
Metal - Steel - General	Generic Models	0.14 m^3	7850	1105.743
Metal - Steel - General	Structural Framing	2.92 m^3	7850	22917.321
Grand total: 906		10522.05 m^3		26321504.294

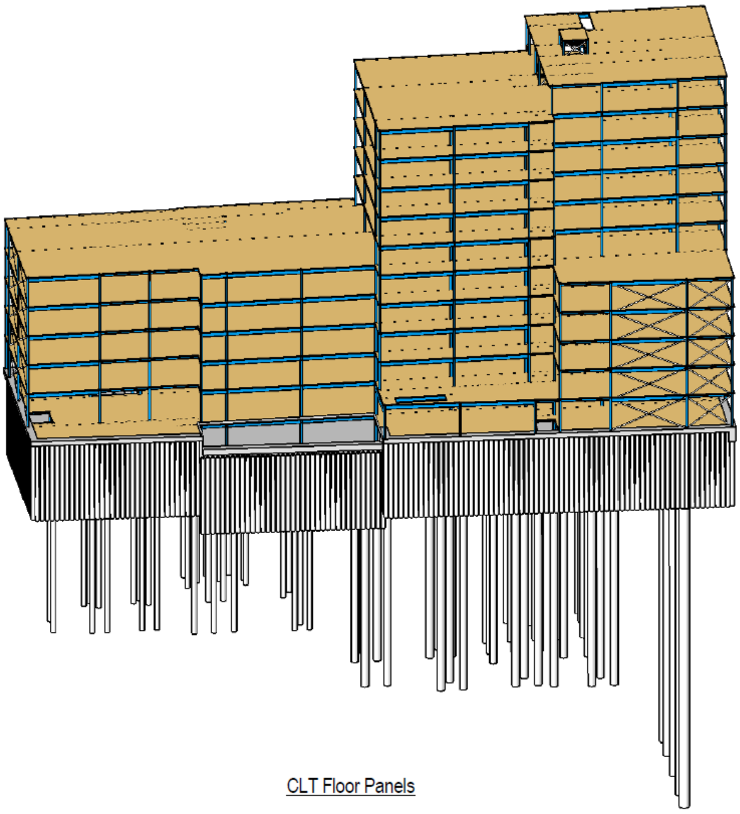
Figure 13 - Scenario 0.0: Base Case



- 275mm thk PT slab
- No downstand beams required
- Stability provided through concrete shear walls
- Roughly same number of piles than flat slab option

Material	Category	Total Volume	Material Density	Weight (kG)
Concrete - Cast In Situ				
Concrete - Cast In Situ	Floors	1890.15 m^3	2500	4725383.216
Concrete - Cast In Situ	Structural Columns	227.28 m^3	2500	568198.131
Concrete - Cast In Situ	Structural Foundations	698.33 m^3	2500	1745837.323
Concrete - Cast In Situ	Walls	939.51 m^3	2500	2348785.257
Concrete - Precast Concrete				
Concrete - Precast Concrete	Floors	3712.64 m^3	2500	9281610.804
Concrete - Precast Concrete	Structural Columns	0.00 m^3	2500	0.000
Concrete - RC Pile				
Concrete - RC Pile	Structural Foundations	2397.55 m^3	2500	5993876.900
Metal - Steel - General				
Metal - Steel - General	Generic Models	0.14 m^3	7850	1105.743
Metal - Steel - General	Structural Framing	2.93 m^3	7850	23032.644
Grand total: 1008		9868.55 m^3		24687830.016

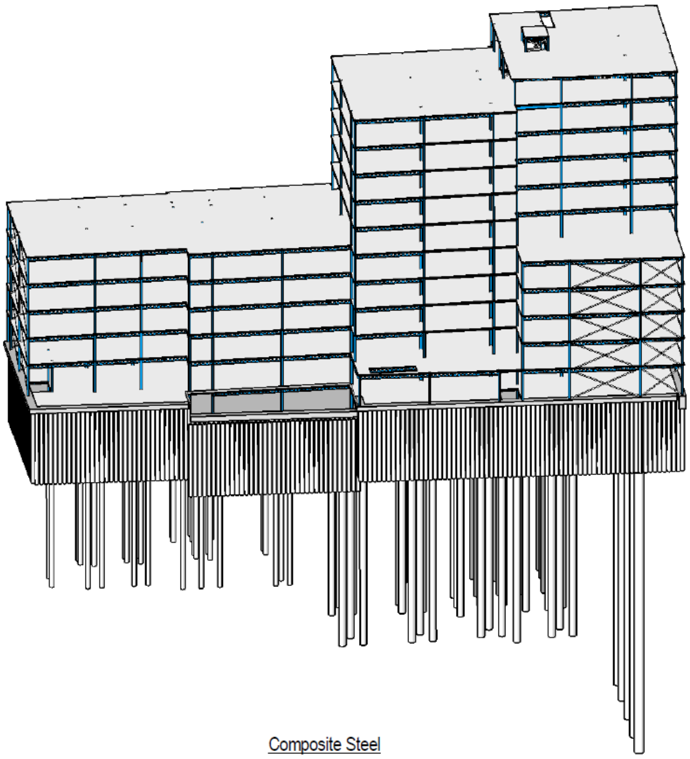
Figure 14 - Scenario 1.1: Lighter Concrete Structure



- 100mm thk CLT panels
- 550mm dp primary and secondary beams
- Secondary beams at 3m crs
- Stability provided through cross bracing
- Roughly 2/3 number of bearing piles than concrete options

Material	Category	Total Volume	Material Density	Weight (kG)
Concrete - Cast In Situ				
Concrete - Cast In Situ	Floors	1349.09 m^3	2500	3372714.255
Concrete - Cast In Situ	Structural Foundations	342.12 m^3	2500	855289.061
Concrete - Cast In Situ	Walls	214.14 m^3	2500	535357.490
Concrete - RC Pile				
Concrete - RC Pile	Structural Foundations	1757.04 m^3	2500	4392593.381
Metal - Steel - General				
Metal - Steel - General	Structural Columns	29.34 m^3	7850	230304.455
Metal - Steel - General	Structural Framing	107.33 m^3	7850	842525.044
Metal - Steel - S275				
Metal - Steel - S275	Structural Framing	2.94 m^3	7850	23101.596
Wood - Dimensional Lumber				
Wood - Dimensional Lumber	Floors	1534.82 m^3	450	690668.042
Grand total: 2377		5336.81 m^3		10942553.324

Figure 15 – Scenario 1.2: Lightweight Cross-Laminated Timber Structure (CLT)



- 130mm thk Comflor60 composite desk gauge 1.2
- Secondary beams at 3m crs
- Stability provided through cross bracing
- Roughly 2/3 number of bearing piles than concrete options

Material	Category	Total Volume	Material Density	Weight (kG)
Concrete - Cast In Situ				
Concrete - Cast In Situ	Floors	1334.98 m^3	2500	3337450.615
Concrete - Cast In Situ	Structural Foundations	302.84 m^3	2500	757087.948
Concrete - Cast In Situ	Walls	211.50 m^3	2500	528749.764
Concrete - RC Pile				
Concrete - RC Pile	Structural Foundations	1814.08 m^3	2500	4535195.044
Metal - Steel - General				
Metal - Steel - General	Structural Columns	32.87 m^3	7850	258003.432
Metal - Steel - General	Structural Framing	77.05 m^3	7850	604807.486
Metal - Steel - S275				
Metal - Steel - S275	Structural Framing	2.93 m^3	7850	22981.774

Composite Decking	Category	Total Volume	Material Density	Area	Weight (kG)
Concrete - cast in Situ (130dp)	Floors	1501.13 m^3	2500	15396 m^2	3752826
Metal - Decking - Gauge 1.2	Floors	28.05 m^3	7850	15396 m^2	220163

Figure 16 - Scenario 1.3: Composite Floor (Metal Deck) and Steel Frame Construction

7.4 Inputs for Scenarios 2.1-2.2 – Sustainable Materials

Table 14 - Scenario 2.1_Maximize Recycled Materials Inputs and Assumptions in detail

Building Element – 2.1 Maximize Recycled Materials	Construction	Assumptions
Foundation (Deep Piles), Pile Caps, Columns, Beams, Lintels, Stairs, Ground Floor Slab, Internal Slabs, Roof and External Walls (basement only)	**Reinforced concrete (RC35) with 30% pulverized fly ash;**	Structural strength of original RC and proposed RC mix with fly ash component is consistent
External Walls (including basement)	100mm Composite: Reclaimed brick and Mortar 184mm Corkboard insulation 15mm Particleboard general sheet 5mm Adhesive for plasterboard 15mm Plasterboard sheet	Thermal performance of reclaimed versus fired bricks is consistent
Ground floor slab and external walls	Replacement of XPS insulation (HFC blown) with corkboard insulation	Insulation conductivity: XPS: 0.03W/mK Corkboard: 0.04W/mK

Table 15 - Scenario 2.2_Earth Constructed Infill Elements Inputs and Assumptions in detail

Building Element – 2.2 Earth Constructed Infill Elements	Material Quantities	Construction (exterior to interior layers)	U-Value (W/m^2K)	Assumptions
External Walls Thickness Total Volume	**0.440m** 1,751m^3	200mm Stabilized rammed earth (pneumatically rammed – 50% on site) 138mm Rigid sheet insulation (XPS) 15mm Particleboard general sheet 75mm Timber framework 12mm Plywood (softwood) sheet	0.1806	Site soil is adequate to source at least 50% of the rammed earth on-site
Internal Partitions Thickness	**0.100m**	12mm Plywood (softwood) sheet 75mm Timber framework 12mm Plywood (softwood) sheet	1.1380	Carbon capture is included for timber products
Windows with Frames Thickness Total Surface Area	**0.360m** 2,975m^2	20% Softwood window frame 18mm Outer glazing pane 12mm air-filled cavity 6mm Inner glazing pane	1.4467	
Hardscape Total Surface Area	1,778m^2	103mm Composite: Stone hard surfacing with mortar	-	-

7.5 Inputs for Scenarios 3.1-3.2 – Sustainable Building Systems

Table 16 – 3.1 Renewables: Literature-Based-Discovery of Life Cycle Data for PV modules

Author	Climate Year	Embodied Energy (MJ/m^2)	Embodied Carbon ($kgCO_2/m^2$ - $gCO_{2\text{-}eq}/kWh$ - gCO_2/kWh)	Energy Payback Time (years)	PV Type or System Size	System Boundary
Pacca et al.[55]	**USA/ Europe 2007**	**2395.01**	**54.6 $gCO_{2\text{-}eq}/kWh$**	**7.5**	**Polycrystalline, BOS[9] 33kW system**	**Cradle to Site + Installation**
Hammond and Jones [80]	UK 2008	4070 (1945 to 5660)	208 (99 to 289)$kgCO_2/m^2$	/	Polycrystalline	Cradle to Gate
Blakers and Weber [57]	Australia 2000	3816	240 $gCO_{2\text{-}eq}/kWh$ (present) 40 $gCO_{2\text{-}eq}/kWh$ (2010)	6.9	/	Cradle to Site + Installation
Fthenakis et al.[81]	SouthEurope 2008	915	30-52 $gCO_{2\text{-}eq}/kWh$	2.5	Polycrystalline module only	Cradle to Gate
Alsema and Nieuwlaar [94-95]	Europe/ Holland 2000	5400	50 gCO_2/kWh (present) 20 gCO_2/kWh (2010)	3.2	Polycrystalline, frame, BOS	Cradle to Site
Bankier and Gale [54]	2006	6400	/	3.8	Polycrystalline, frame, BOS,	Cradle to Site + Installation
Jungbluth[56] (ecoinvent)	Switzerland 2005	/	39-110 $gCO_{2\text{-}eq}/kWh$	3-6	Polycrystalline	/

[9] Balance of Support of PV: includes, module supports, cabling, inverter and power conditioning etc.

Table 17 – 3.1 Renewables Inputs and Assumptions for Renewables in detail

Photovoltaic System Specifications	Units	Inputs	Reference
Size of PV Module - Length	m	1.65	**Solar World Product Sunmodule+ SW 245** [82] http://www.solarworld-uk.co.uk/fileadmin/downloads_new/produkt/sunmodule/broschueren/pv-test-2013-en.pdf
Width	m	1	
Area/Module	m^2	1.65	
Weight	kg/module	18	
Total Weight	kg	18kg * 31 modules= 558kg	
Cell type	type	Polycrystalline	
Expected Lifetime	years	30	
Specific power	W	245	
Efficiency under STC (1000W of solar radiation per m^2, 25°C measured)	%	14.53	
System Size	kW	8	Project Specifications
Area of Building (GIFA)	m^2	15,197	
Total Module Area	m^2	50	
Functional Unit (NIA)	m^2	11,500	
Number of Modules	#	31	Calculated
Total System Weight (+30% BOS weight)	ton	0.725	Calculated
Photovoltaic System Output Data			
Yearly Energy Produced by PV	kWh/m^2 GIFA year	0.35	BRUKL Output Document - IES VE Compliance w. UK regulations Part L 2013
Yearly PV Output	kWh/year	5,318	
Photovoltaic System Embodied Data			
PV Embodied Energy	MJ/m^2 (module)	2,395	Pacca et al. 2007 [55]
PV Embodied Carbon	$gCO_{2\text{-}eq}/kWh$	54.6	
Energy Payback Period	years	7.5	
Feed-In-Tariff	£/year	495	Energy Saving Trust [83]; Department of Energy and Climate [84]
Carbon savings	$kgCO_2$/year	1870	
System cost (of a typical 4kW system)	£/system	5,000-8,000	
Solar PV Cost Per Unit Power	£/kWp	1,537	
Cost Payback Time	years	10.1-16.2	
Cradle-to-Gate* PV Embodied Energy/NIA	**MJ/m^2**	2* [2,395MJ/m^2 * 50m^2/NIA]= **239,500 MJ/NIA= 20.82 MJ/m^2**	**Calculated** [55]
Cradle-to-Gate* PV Embodied Carbon/NIA	**$kgCO_{2\text{-}eq}/m^2$**	2* [54.6$gCO_{2\text{-}eq}$/kWh * 5,318kWh/year * 30 years/NIA]= **17,421.77$kgCO_{2\text{-}eq}$/NIA= 1.51$kgCO_{2\text{-}eq}/m^2$**	**Calculated** [55]
Total System Capital Cost/NIA	**£/m^2**	2* [8kW * 1,537£/kW/NIA]= **24,592.00£/NIA= 2.14£/m^2**	**Calculated** [84]
Transport Embodied Data			
Manufacturer (Bonn) to Port of Cologne Port of Cologne to Port of Tilbury Port of Tilbury (London) to Project Site	miles	16.65 - land 381 – sea 26.6 - land	Google Maps
Embodied Energy Road Transport	MJ/tonne-mile	3.87	Hammond and Jones 2011 [85]
Embodied Energy Oceanic Shipping	MJ/tonne-mile	0.24	
Embodied Carbon Road Transport	$kgCO_{2\text{-}eq}$/tonne-mile	0.24	
Embodied Carbon Oceanic Shipping	$kgCO_{2\text{-}eq}$/tonne-mile	0.0145	
Gate-to-Site[10;11] PV Embodied Energy/NIA	**MJ/m^2**	2 * [43.25miles * 3.87MJ/tonne-mile + 381miles * 0.24MJ/tonne-mile] * 0.558tonne/NIA= **288.84MJ/NIA= 0.025MJ/m^2**	**Calculated**
Gate-to-Site* PV Embodied Carbon/NIA	**$kgCO_{2\text{-}eq}/m^2$**	2 * [43.25miles * 0.24$kgCO_{2\text{-}eq}$/tonne-mile + 381miles * 0.0145 $kgCO_{2\text{-}eq}$/tonne-mile] * 0.558tonne/NIA= **17.75 $kgCO_{2\text{-}eq}$/NIA= 0.0015 $kgCO_{2\text{-}eq}/m^2$**	**Calculated**

[10] If the study period is 60 years – and the PV life time is 30 years (then they have to be replaced 2x)

[11] Assumptions: No extra PV considerations are added as a result of waste during the transport stage

Table 18 – Scenario 3.2-CHP: Limited Literature Found for Embodied Carbon and Energy Data of CHP Systems

Author	Climate Year	Embodied Energy (GJ)	Embodied Carbon (tonneCO_2)	Lifetime (years)	CHP Type or System Size	System Boundary
Gazis and Harrison [63]	UK/Norway 2011	13.3 - 19.0	0.86-1.28	15	Domestic 1kW Power/ 24kW Heat	Cradle-to-Grave
Lansche and Müller [64]	Germany 2012	/	3.38	30	Industrial (varying scale) 50-2000kW	Cradle-to-Grave

Table 19 – Scenario 3.2-CHP: Inputs and Assumptions of Embodied Impact Data for CHP Systems

Life Cycle Phase [63]	Embodied Energy (GJ)	Embodied Carbon (tonneCO_2)
Total Embodied	76	5.12
Raw Materials	11.1	0.7
Machining and Assembly	0.1	0.02
Transport	0.7	0.05
Maintenance	6.9	0.5
Replacements	3*19=57	3*1.28=3.84
End of Life	0.15	0.01

7.6 Scenario 5.0 – Final Cumulative Scenario with Maximum Life Cycle Savings

Table 20 - Scenario 5.1_Cumulative Savings Inputs and Assumptions in detail

Building Element – 5.1 Cumulative Savings		Material Quantities	Construction (exterior to interior layers)	U-Value (W/m²K)
Structural Elements	**Foundation** (**Deep Piles**) Structural Volume	**1,950m³**	Concrete: RC35; with 30% PFA Steel reinforcement: 2.10%	-
	Contiguous Piles Structural Volume	**448m³**	Concrete: RC35; with 30% PFA Steel reinforcement: 2.10%	-
	Pile Caps Structural Volume	**698m³**	Concrete: RC35; with 30% PFA Steel reinforcement: 2.10%	-
	Column Structural Volume Column Spacing (Grid)	**227m³** 9m x 9m	Concrete: RC35; with 30% PFA Steel reinforcement: 3.25%	-
	Beams/Structural Framing Structural Volume	**None** (flat slab construction)	-	-
	Lintels Structural Volume	**71m³**	Concrete: RC35; with 30% PFA Steel reinforcement: 2.1%	-
	Stairs Structural Volume	**45m³**	Concrete: RC35; with 30% PFA Steel reinforcement: 3.25%	-
	Basement Slab Structural Volume	**982m³**	245mm Corkboard insulation 400mm Composite: RC35; with 30% PFA (2.10% steel reinforcement) 20mm Chipboard sheet	0.1210
	Internal Slab Structural Volume	**3,713m³**	50mm Carpet tiles 275mm Composite: RC35; with 30% PFA (2.10% steel reinforcement)	0.1673
	Roof Structural Volume	**908m³**	2.5mm Roof membrane (bituminous) 0.3mm Vapour control layer 1mm Roof deck 270mm Corkboard insulation 400 Composite: RC35 (2.10% steel reinforcement)	0.1222
	Internal Shear Wall		12mm Plywood (softwood) sheet	1.6811

	Structural Volume	**940m³**	70mm Timber framework 160mm Composite: Block concrete (recycled), mortar and steel reinforcement (2.1%)	
Non-Structural Elements	**External Walls** Thickness Total Volume	**0.380m** 1215m³	100mm Composite: Brick (reclaimed) and Mortar 178mm Corkboard insulation 15mm Particleboard general sheet 75mm Timber framework 12mm Plywood (softwood) sheet	0.1810
	External Walls (Basement) Thickness Total Volume	**0.472m** 318m³	145mm Corkboard insulation 225mm Composite: RC35 (2.10% steel reinforcement) 15mm Particleboard general sheet 75mm Timber framework 12mm Plywood (softwood) sheet	0.1869
	Internal Partitions Thickness	**0.100m**	12mm Plywood (softwood) sheet 75mm Timber framework 12mm Plywood (softwood) sheet	1.2739
	Windows with Frames Thickness Total Surface Area	**0.360m** 2,975m²	20% Wooden window frame 18mm Outer glazing pane 12mm air-filled cavity 6mm Inner glazing pane	1.4467
	Hardscape Total Surface Area	1,778m²	75mm Asphalt paving over prepared sub-base	-
Operational Strategies	**PV**	Adopted from Scenario 3.1		-
	CHP	Adopted from Scenario 3.2		-
	Temperature Set-points	Adopted from Scenario 4.2		-
	Natural Ventilation	Adopted from Scenario 4.2		-
	Louvers for Shading	Adopted from Scenario 4.3		-

1